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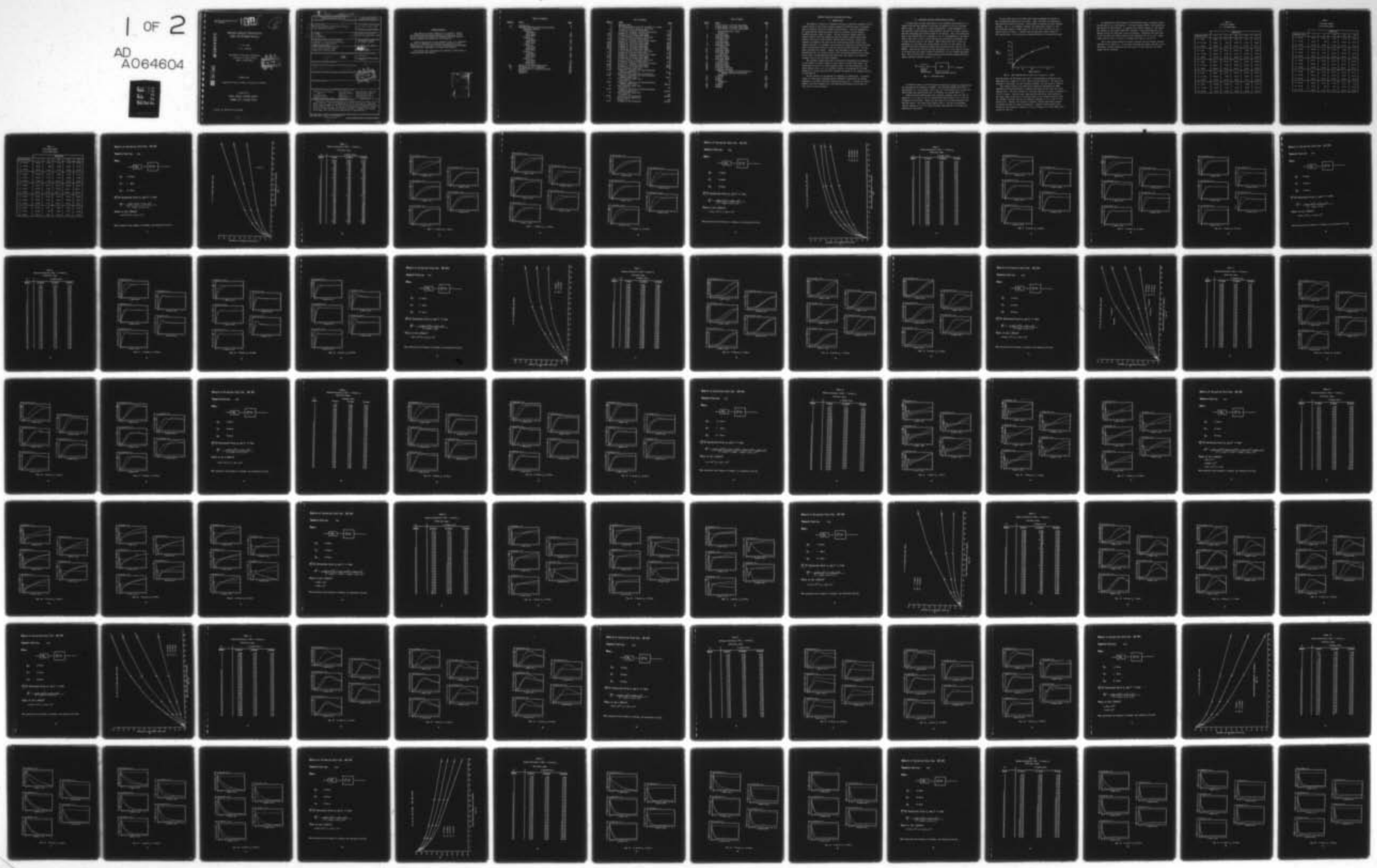

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NONLINEAR HANDLING CHARACTERISTICS MODEL FOR SUBMERGED VEHICLES

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Transfer function
Side-slip
Plunge velocity
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Normalization: amplitude
Normalization: speed
Normalization: CNL
Parametrization of TF coefficients

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Nonlinear models are developed for the handling-characteristics of submerged vehicles. This is accomplished by use of a cascade of a nonlinear gain, custom designed to fit the vehicle's saturation characteristics, and a linear transfer function. The latter is obtained by application of 'GRAM Identifier' upon the vehicle's transient response. Validity over typical speed ranges and control surface excursions, is demonstrated.

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IMPROVED HANDLING-CHARACTERISTICS MODEL

I. INTRODUCTION

The dynamics of motion of underwater vehicles is basically nonlinear [1]-[4]. A major thrust of this year's research supported by NCSC has been the development of nonlinear models of handling characteristics. This was accomplished by separating the steady-state gain, which is nonlinear, and the dynamic transfer function, which is linear. The two, placed in tandem, model the vehicle behavior over wide ranges of speed and control surface deflections. Further, the poles of this transfer function more accurately reflect the vehicle's performance than those of the traditionally used strictly linear transfer function. For example, the poles of the traditional transfer function tend to show greater stability than the vehicle actually possesses. The new model overcomes this defect. Indeed, this refinement in handling qualities description will, it is hoped, yield a truer correlation between pilot rating of the craft, the handling qualities model and, when desired, the simulator response of the craft for pilot training.

The nonlinear steady-state gain is obtained by determining the responses of the vehicle to various degrees of step inputs, say the rudder input, and computing the ratio of the final response value to the input magnitude. The linear dynamic part, i.e., the transfer function, is determined by the GRAM Identifier, a system identification technique developed in the research efforts of 1974-1976 [5].

We will develop the methodology for modeling and demonstrate its application to a particular submerged vehicle (USFRPV) by generating the vehicle responses on the NCSC trajectory simulation program [5]. It should be obvious, however, that the ultimate use of the modeling methodology will be upon tow tank tests of actual vehicles.

II. NONLINEAR HANDLING-CHARACTERISTICS MODELS

To find a more accurate description of the handling characteristics of a vehicle than has been achieved in the past, we propose to use the structure shown in Fig. 1. Here CNL is a static nonlinearity, custom designed to fit the vehicle's actual saturation characteristic, and H(s) is a linear transfer function describing the transient modes of the vehicle. Since the steady-state gain of H(s) (namely H(0)) is a constant, i.e., it is independent of the amplitude of the input to H(s), the CNL function can be found by performing a set of step function tests on the vehicle. While these tests can of course be performed in a tow-tank on an actual vehicle, we will, in this report, use the NCSC trajectory simulation program upon a particular test vehicle, the USFRPV. Once the CNL function has been determined, say in the form of a table, it is shown that the linear transfer function H(s), or its z-domain equivalent H(z), can be found by use of a linear system identification program developed under a previous research contract [5], [6].

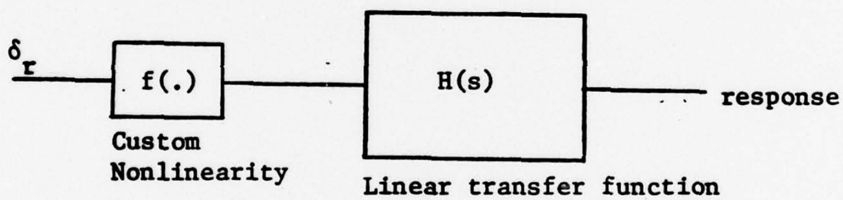


Fig. 1. Nonlinear model

As mentioned above, the NCSC Trajectory Simulation Program is utilized here for determining the responses of USFRPV. The following changes were made in the program: (i) the uu terms, such as K_{uu} etc., were zeroed out, and (ii) the vehicle speed was synthetically set to a constant (by setting XD(1) = 0).

After the above modifications were completed, computer runs were made at speeds of 5, 7.5, 10, 15, 20, 25, 30 knots with rudder inputs of 1, 5, 10, 20, 35 degrees at each speed. These runs were made for a 40 second duration with 200 data points. The rudder input shown in Fig. 2, and the corresponding vehicle responses V, W, P, Q, R were obtained (and punched on card decks for modeling and analysing).

To form a CNL table, the steady state value of response is plotted vs. the corresponding amplitude of step input. Thus a CNL table is obtained for each particular speed of interest. This process is repeated for each response variable. Fig. 2, for example, displays the steady state values of v for five different values of rudder steps (1°, 5°, 10°, 20°, and 35°), all for a vehicle speed of 5 knots. A smooth curve through these points yields the CNL characteristic of the particular response variable at the specified speed.

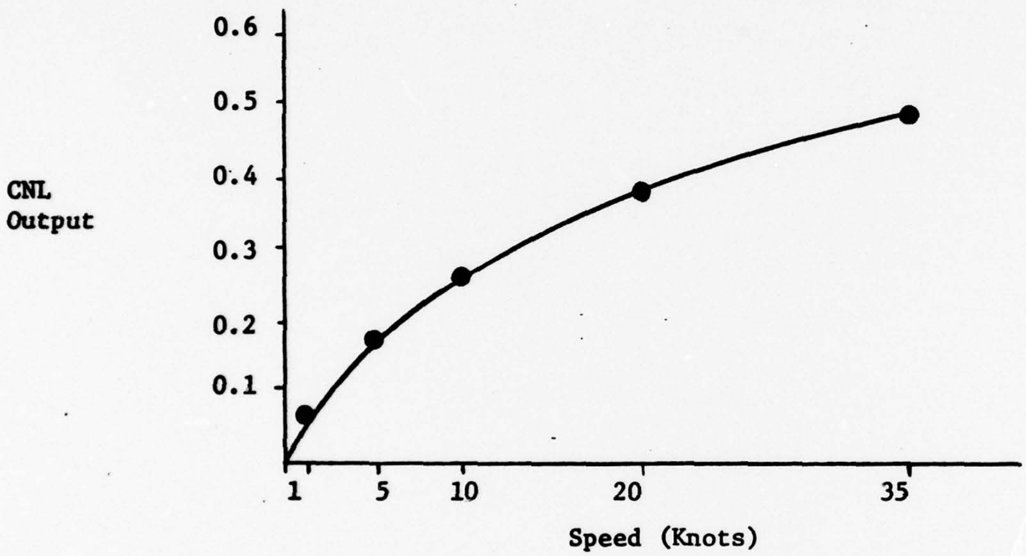


Fig. 2. CNL characteristics curve for V versus δ_r, 5 knots

From the graph, the CNL Output (see Fig. 2) corresponding to different input amplitudes over a range of 0 to 36° can be read and tabulated. CNL tables are prepared in this manner for each response variable, one each speed of interest.

The transfer function for each motion variable is determined via GRAM identifier, mentioned previously, using the CNL table and the input and output response data. The input pertains to the rudder whereas the output corresponds to V, W, P, Q and R. The CNL value, taken from the CNL table, corresponding to the input rudder deflection is the actual input to the transfer function block The transfer functions used for the response variables V, W, Q, R are of the second order. However, the variable P requires a fourth order model because of visible presense of a double oscillation. Transfer function models were formed for all variables of speeds of 7.5, 15, 25 knots; a 5° step rudder input as used in each run.

To determine the effectiveness of the identified model a validation phase was included in our investigation. A Fortran program, VERIFY, (see Appendix A) was written for this purpose. It predicts the vehicle response to test inputs and compares it with actual (NCSC TSP) response. Plots exhibiting this comparison as well as a RMS error value are obtained. Validation runs were made at (a) the speed the transfer function was developed, call it U_o, (b) a speed higher than U_o, call it U+ and (c) a speed lower than U_o, call it U-.

The % total energy between the vehicle response and the transfer function response are in Tables 1-3. In the pages following the tables, the CNL curves, CNL Tables, and the validation plots are given for each speed for all speed ranges and all variables.

Table 1

% OF TOTAL ENERGY

5 - 10 SPEED RANGE

	DEFLECTION				
VARIABLE-SPEED	1°	5°	10°	20°	35°
V - 5 Kn	39.87	17.61	4.82	6.47	11.37
V - 7.5 Kn	26.83	.144	10.04	17.17	19.94
V - 10 Kn	16.29	9.65	17.03	22.39	24.27
W - 5 Kn	78.73	37.94	22.34	5.40	8.80
W - 7.5 Kn	38.63	2.20	17.32	30.47	37.01
W - 10 Kn	19.94	23.48	36.85	33.99	48.39
P - 5 Kn	111.0	63.41	24.81	45.52	54.84
P - 7.5 Kn	105.3	6.88	39.86	60.48	58.52
P - 10 Kn	98.85	25.52	49.12	61.64	47.88
Q - 5 Kn	111.9	57.67	19.14	22.62	31.44
Q - 7.5 Kn	83.61	3.99	31.31	43.50	40.37
Q - 10 Kn	55.05	24.22	40.60	45.11	42.08
R - 5 Kn	35.56	12.89	1.42	8.89	12.77
R - 7.5 Kn	21.02	0.47	9.33	15.81	18.17
R - 10 Kn	17.52	6.99	13.99	19.16	20.94

Table 2

% OF TOTAL ENERGY

10-20 SPEED RANGE

	DEFLECTION				
VARIABLE-SPEED	1°	5°	10°	20°	35°
V - 10 Kn	37.94	11.05	3.26	3.73	6.25
V - 15 Kn	21.62	.412	6.07	11.07	13.83
V - 20 Kn	11.28	6.46	11.54	15.71	21.15
W - 10 Kn	94.99	35.17	15.80	5.38	6.97
W - 15 Kn	47.33	2.44	11.63	19.20	21.36
W - 20 Kn	19.19	14.45	21.99	26.67	26.26
P - 10 Kn	137.5	23.33	32.50	42.27	24.59
P - 15 Kn	95.84	3.30	17.56	15.76	165.92
P - 20 Kn	84.92	31.19	49.85	161.0	137.5
Q - 10 Kn	104.8	21.36	15.63	11.31	14.71
Q - 15 Kn	59.34	3.52	14.45	27.19	42.35
Q - 20 Kn	41.63	20.07	30.68	40.70	50.20
R - 10 Kn	33.68	8.48	1.51	5.24	7.54
R - 15 Kn	17.41	.716	5.57	9.97	12.06
R - 20 Kn	12.63	4.94	9.31	13.34	15.92

Table 3

% OF TOTAL ENERGY

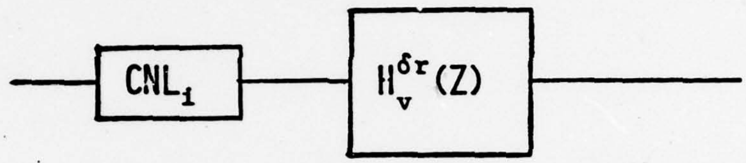
20-30 SPEED RANGE

	DEFLECTION				
VARIABLE-SPEED	1°	5°	10°	20°	35°
V - 20 Kn	21.89	4.99	1.24	5.17	11.60
V - 25 Kn	15.36	.405	4.88	10.11	16.70
V - 30 Kn	10.69	3.43	8.17	15.35	17.96
W - 20 Kn	40.29	9.35	2.09	6.84	13.12
W - 25 Kn	24.82	1.29	7.65	13.88	13.60
W - 30 Kn	17.94	7.25	12.94	15.70	19.50
P - 20 Kn	43.44	37.79	28.74	66.59	110.8
P - 25 Kn	35.60	2.86	62.35	113.9	107.5
P - 30 Kn	36.12	59.93	111.4	110.0	106.5
Q - 20 Kn	33.07	11.30	4.92	8.32	18.31
Q - 25 Kn	23.70	2.93	8.50	15.50	13.61
Q - 30 Kn	27.66	7.73	14.65	15.41	18.77
R - 20 Kn	19.42	3.43	1.80	6.25	9.36
R - 25 Kn	13.86	.798	4.66	9.25	10.49
R - 30 Kn	10.44	2.67	7.58	11.54	11.32

RESULTS OF VALIDATION TESTS FOR: USF RPV

TRANSFER FUNCTION: $V/\delta r$

MODEL:



U_o: 7.5 Knots

U_-: 5 Knots

U_+: 10 Knots

$H_v^{\delta r}(Z)$ DETERMINED USING U_o AND 5° δr STEP

$$H_v^{\delta r} = \frac{1.066 \times 10^{-2} Z - 9.772 \times 10^{-3}}{Z^2 - 1.950Z + 9.512 \times 10^{-1}}$$

POLES IN THE S DOMAIN*

$-1.25 \times 10^{-1} \pm j\, 8.49 \times 10^{-2}$

*For conversion from Z-domain to S-domain, see references [11],[8].

5, 7.5, 10 knots V/δr CNL curves

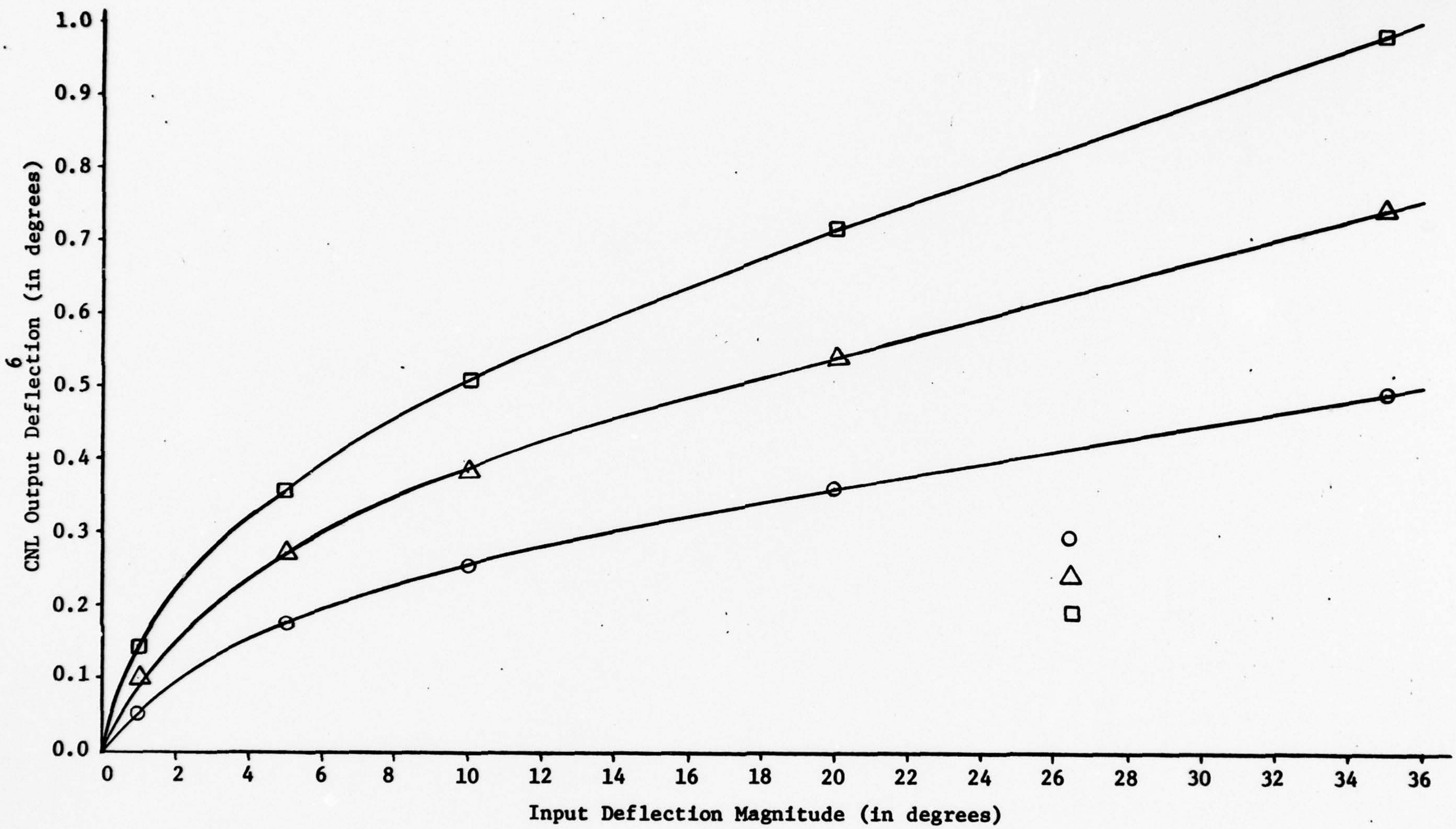


Fig. 3

Table 4

Custom nonlinearity (CNL): V versus δ_r

5-10 knot range

δ_r Degree	V steady state 5 knots	7.5 knots	10 knots
0	0.000	0.000	0.000
1	0.055	0.100	0.143
2	.095	0.160	.215
3	.125	.205	.270
4	.155	.240	.316
5	0.180	0.272	0.357
6	.199	.300	0.391
7	.215	.323	.427
8	.232	.345	.455
9	.243	.362	.483
10	0.262	0.385	0.509
11	.270	.400	.533
12	.281	.418	.555
13	.292	.435	.579
14	.305	.450	.600
15	.315	.469	.620
16	.325	.482	.640
17	.335	.500	.660
18	.344	.515	.680
19	.352	.530	.700
20	0.367	0.544	0.720
21	.370	.557	.739
22	.380	.570	.755
23	.389	.582	.771
24	.397	.595	.790
25	.405	.610	.809
26	.413	.622	.823
27	.421	.637	.841
28	.430	.650	.860
29	.440	.662	.877
30	.448	.676	.893
31	.456	.690	.912
32	.465	.700	.930
33	.475	.715	.946
34	.482	.730	.962
35	0.494	0.740	0.980
36	.500	.755	.999

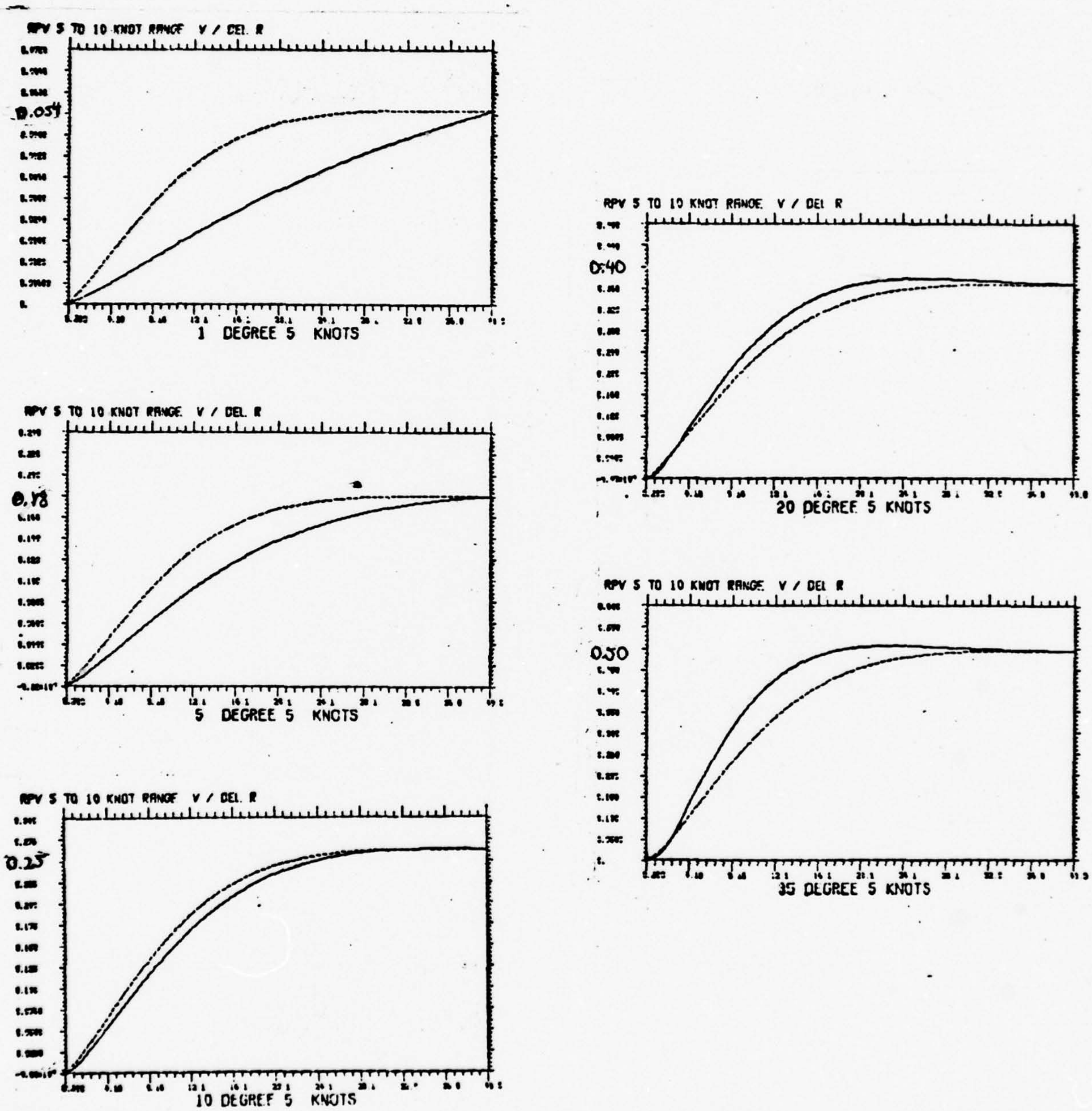


Fig. 4. V Versus δ_r, 5 Knots

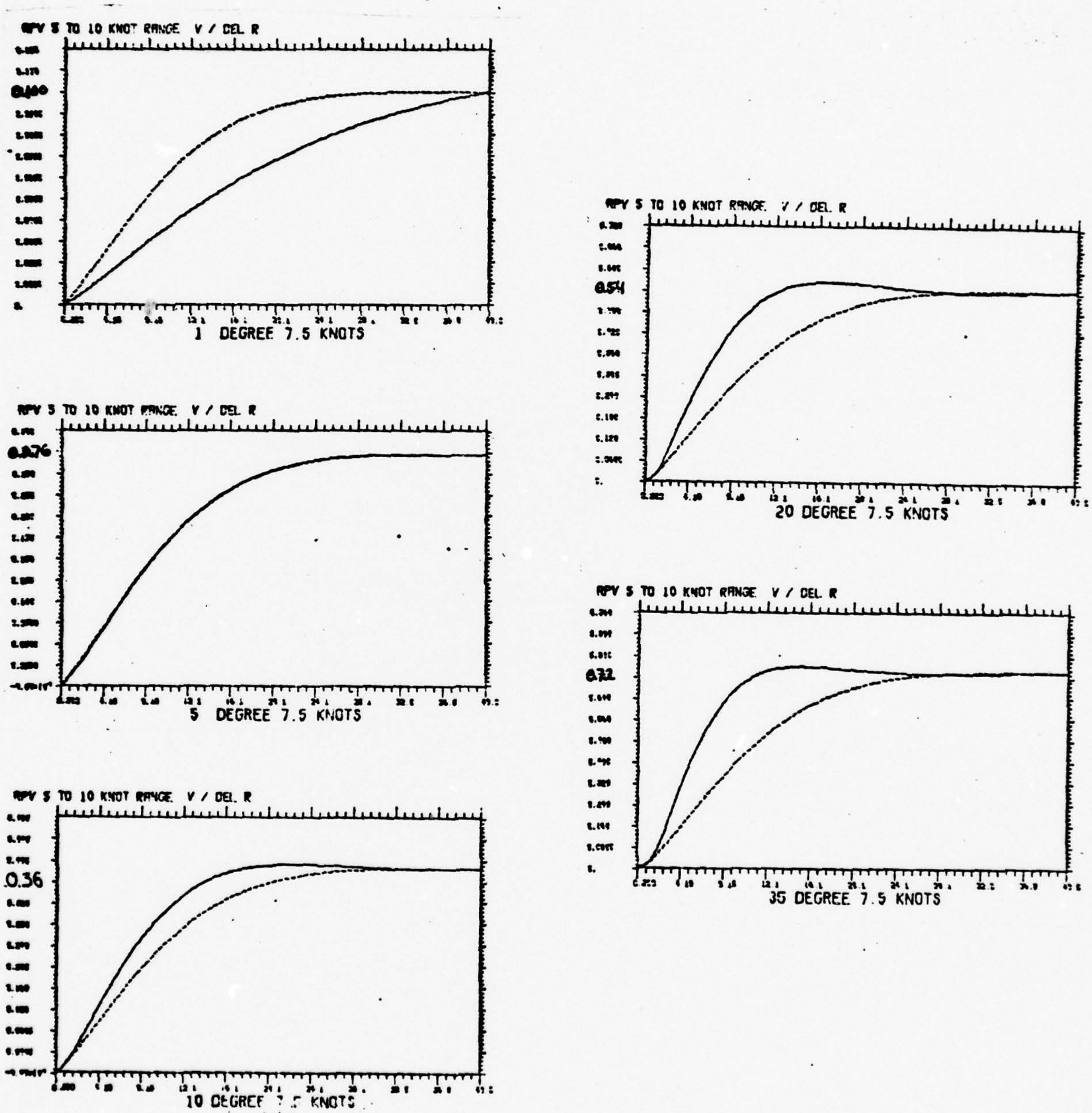
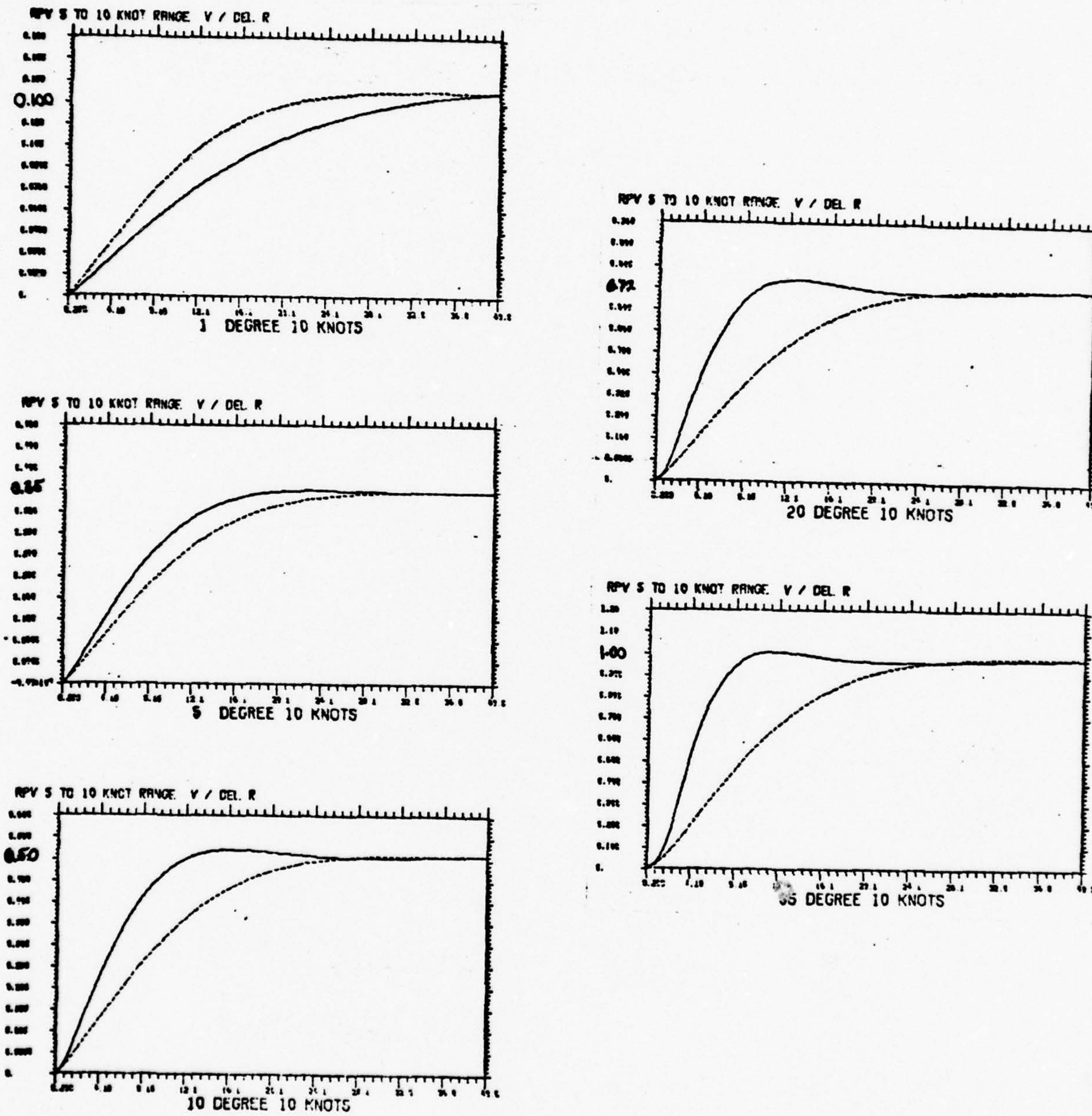


Fig. 5. V Versus δ_r, 7.5 Knots

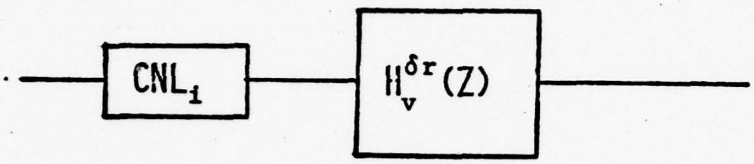


V Versus δ_r, 10 Knots

RESULTS OF VALIDATION TESTS FOR: USF RPV

TRANSFER FUNCTION: $v/\delta r$

MODEL:



U_o: 15 Knots

U_-: 10 Knots

U_+: 20 Knots

$H_v^{\delta r}(Z)$ DETERMINED USING U_o AND 5° δr STEP

$$H_v^{\delta r} = \frac{2.058 \times 10^{-2} Z - 1.696 \times 10^{-2}}{Z^2 - 1.903Z + 9.067 \times 10^{-1}}$$

POLES IN THE s DOMAIN*

$$-2.447 \times 10^{-1} \pm j\, 1.894 \times 10^{-1}$$

*For conversion from Z-domain to S-domain, see references [11],[8].

15, 20, 25, and 30 knot $\underline{V}/\delta_r$ CNL curves

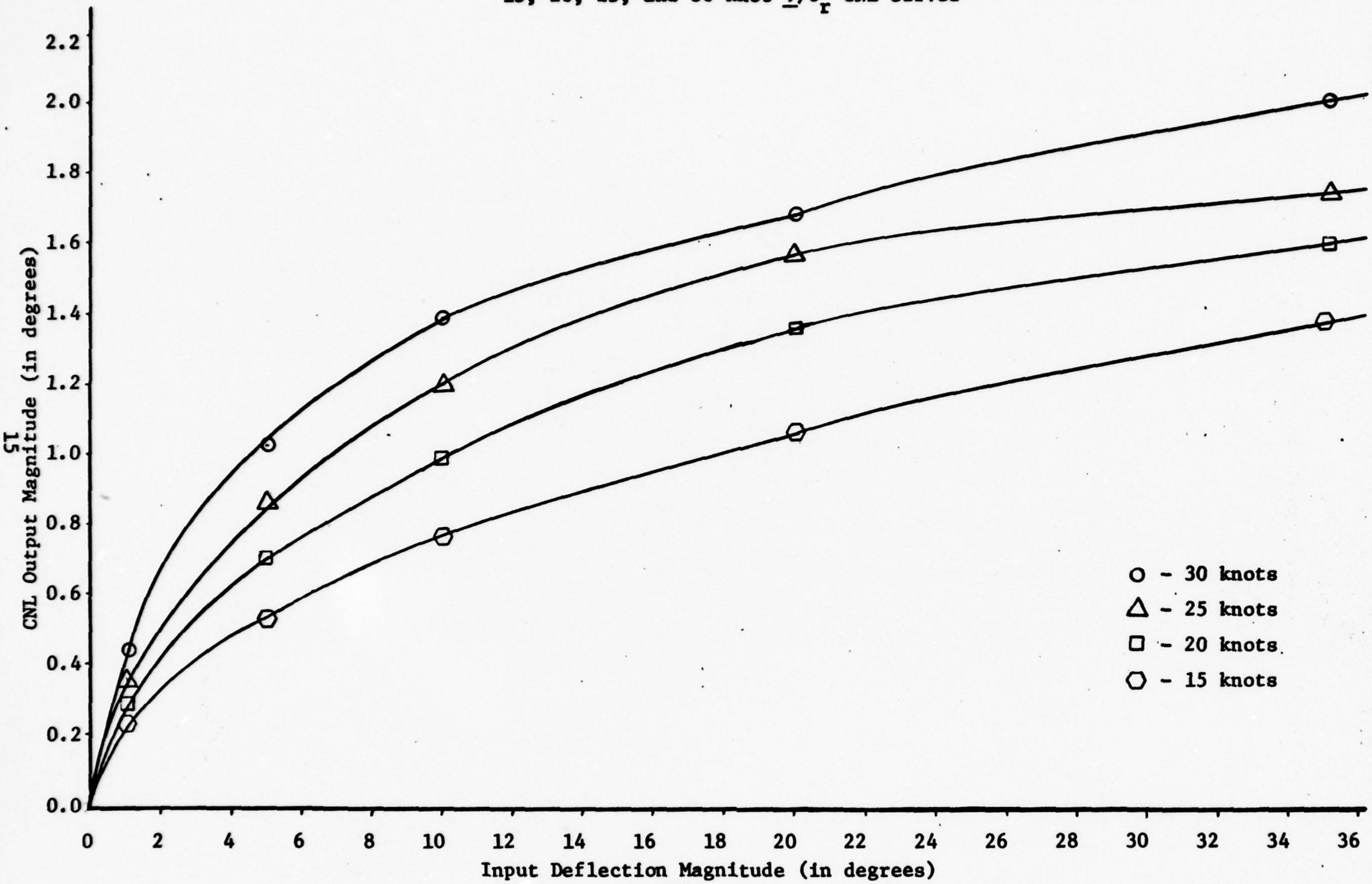


Fig.

Table 5

Custom nonlinearity (CNL): V versus δ_r

10-20 knot range

δ_r	V steady state		
Degree	10 knots	15 knots	20 knots
0	0.000	0.00	0.00
1	0.143	0.22	0.29
2	0.215	0.32	0.43
3	0.270	0.40	0.54
4	0.316	0.47	0.62
5	0.357	0.53	0.70
6	0.391	0.59	0.77
7	0.427	0.64	0.83
8	0.455	0.68	0.89
9	0.483	0.72	0.94
10	0.509	0.76	0.99
11	0.533	0.80	1.04
12	0.555	0.83	1.08
13	0.579	0.86	1.12
14	0.600	0.89	1.16
15	0.620	0.92	1.20
16	0.640	0.95	1.23
17	0.660	0.98	1.26
18	0.680	1.00	1.29
19	0.700	1.03	1.33
20	0.720	1.06	1.36
21	0.739	1.09	1.38
22	0.755	1.12	1.40
23	0.771	1.14	1.42
24	0.790	1.16	1.44
25	0.809	1.18	1.46
26	0.823	1.21	1.47
27	0.841	1.23	1.48
28	0.860	1.25	1.50
29	0.877	1.27	1.52
30	0.893	1.29	1.53
31	0.912	1.31	1.54
32	0.930	1.33	1.56
33	0.946	1.34	1.57
34	0.962	1.36	1.58
35	0.980	1.38	1.59
36	0.999	1.40	1.60

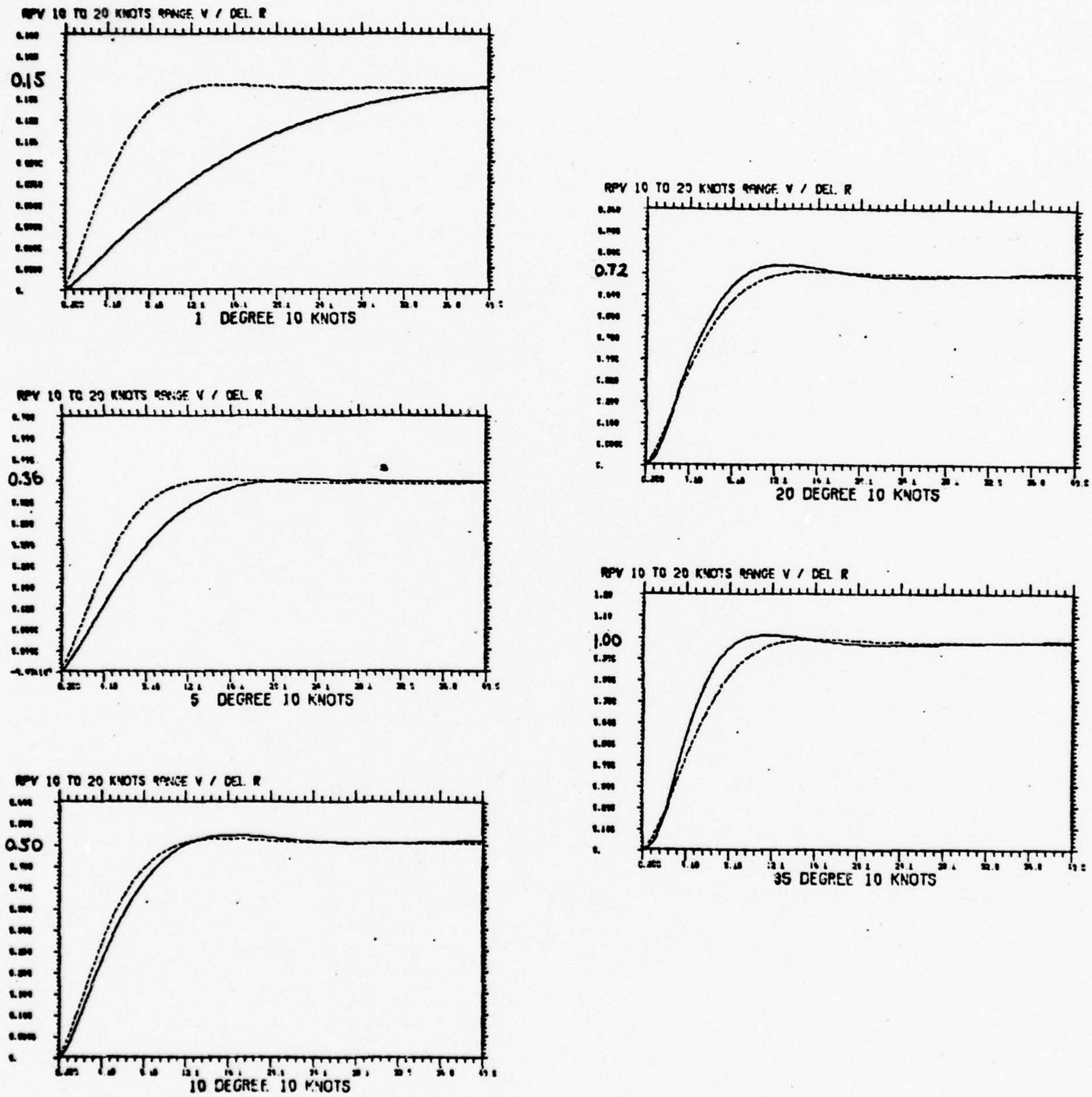


Fig. 8. V Versus δ_r, 10 Knots

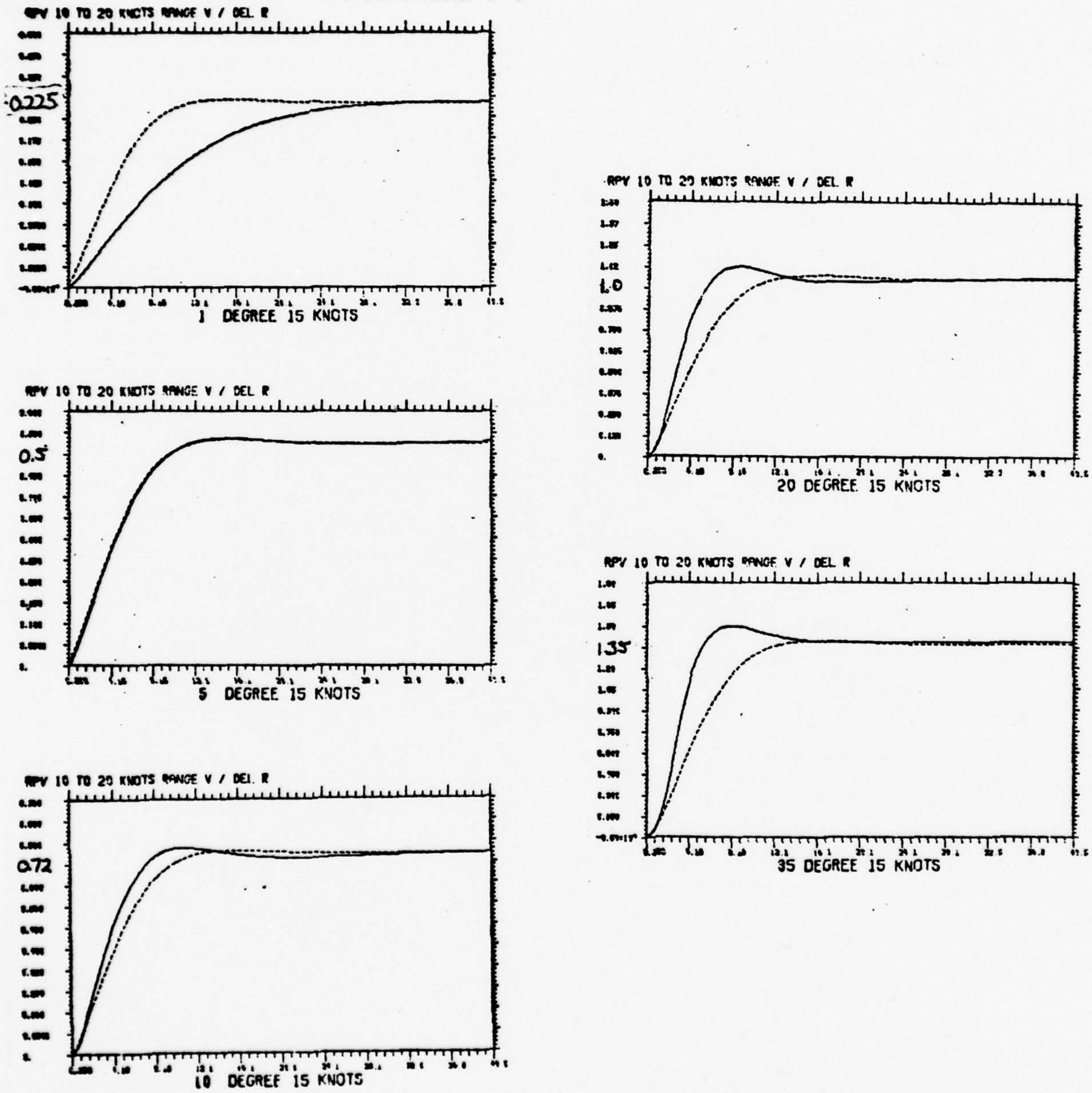


Fig. 9. V Versus δ_r, 15 Knots

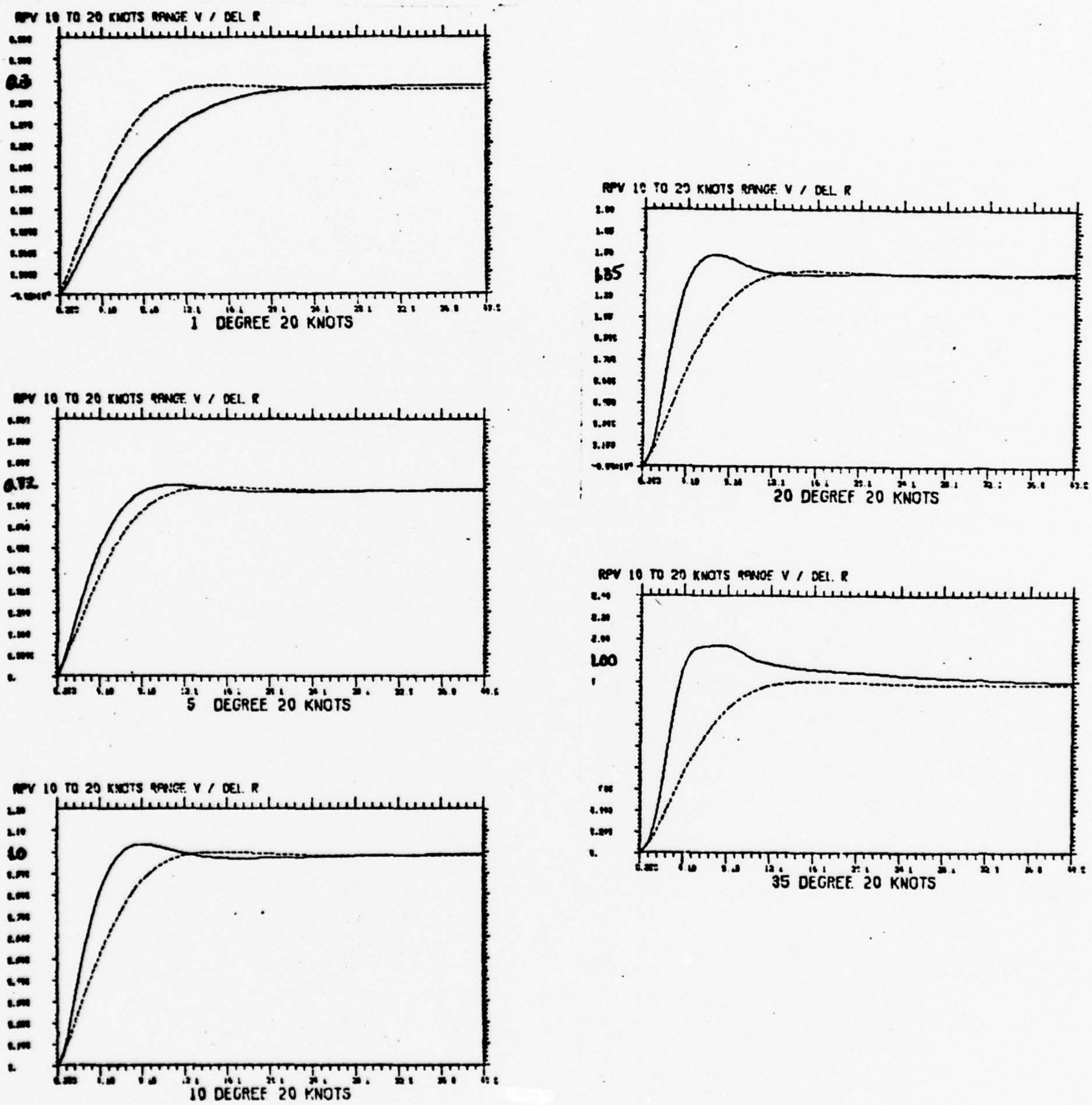
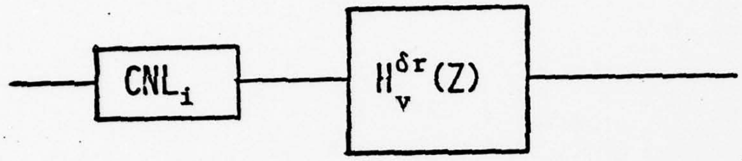


Fig. 10. V Versus δ_r, 20 Knots

RESULTS OF VALIDATION TESTS FOR: USF RPV

TRANSFER FUNCTION: $v/\delta r$

MODEL:



U_o: 25 Knots

U_-: 20 Knots

U_+: 30 Knots

$H^{\delta r}(Z)$ DETERMINED USING U_o AND 5° δr STEP

$$H_v^{\delta r} = \frac{3.557 \times 10^{-2} Z - 2.615 \times 10^{-2}}{Z^2 - 1.854Z + 8.630}$$

POLES IN THE s DOMAIN*

$-3.683 \times 10^{-1} \pm j\ 3.439 \times 10^{-1}$

*For conversion from Z-domain to S-domain, see references [11],[8].

Table 6

Custom nonlinearity (CNL): V versus δ_r

20-30 knot range

δ_r	V steady state		
Degree	20 knots	25 knots	30 knots
0	0.00	0.00	0.00
1	0.29	0.36	0.43
2	0.43	0.54	0.60
3	0.54	0.67	0.87
4	0.62	0.77	0.90
5	0.70	0.86	1.02
6	0.77	0.95	1.12
7	0.83	1.03	1.21
8	0.89	1.08	1.28
9	0.94	1.14	1.34
10	0.99	1.20	1.39
11	1.04	1.25	1.43
12	1.08	1.30	1.47
13	1.12	1.34	1.50
14	1.16	1.38	1.53
15	1.20	1.42	1.56
16	1.23	1.45	1.59
17	1.26	1.48	1.61
18	1.29	1.51	1.64
19	1.33	1.54	1.66
20	1.36	1.57	1.68
21	1.38	1.59	1.71
22	1.40	1.60	1.74
23	1.42	1.62	1.76
24	1.44	1.63	1.78
25	1.46	1.64	1.81
26	1.47	1.65	1.83
27	1.48	1.66	1.85
28	1.50	1.68	1.88
29	1.52	1.69	1.90
30	1.53	1.70	1.92
31	1.54	1.71	1.94
32	1.56	1.72	1.96
33	1.57	1.73	1.98
34	1.58	1.73	2.00
35	1.59	1.74	2.01
36	1.60	1.74	2.03

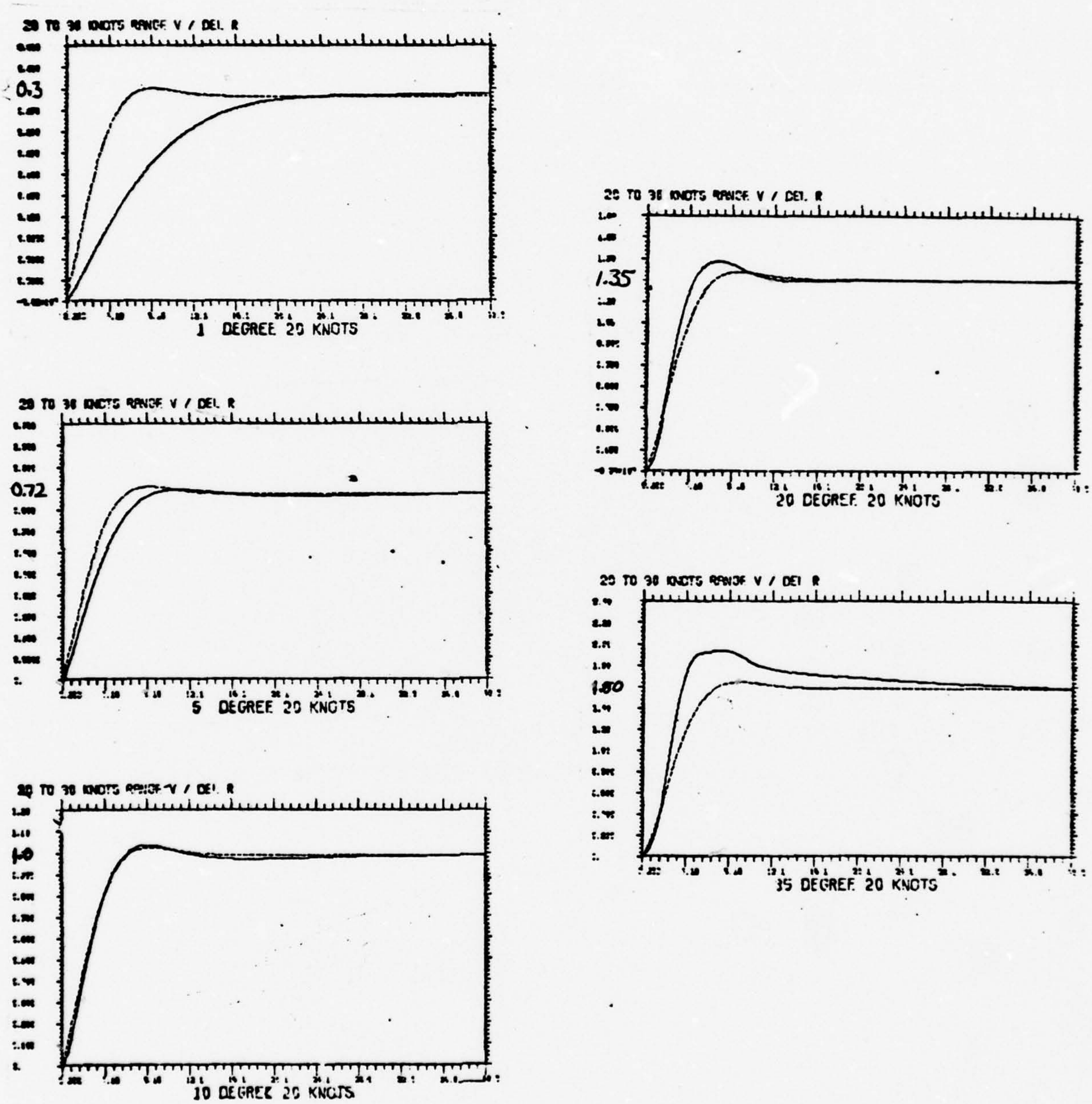


Fig. 11. V Versus δ_r, 20 Knots

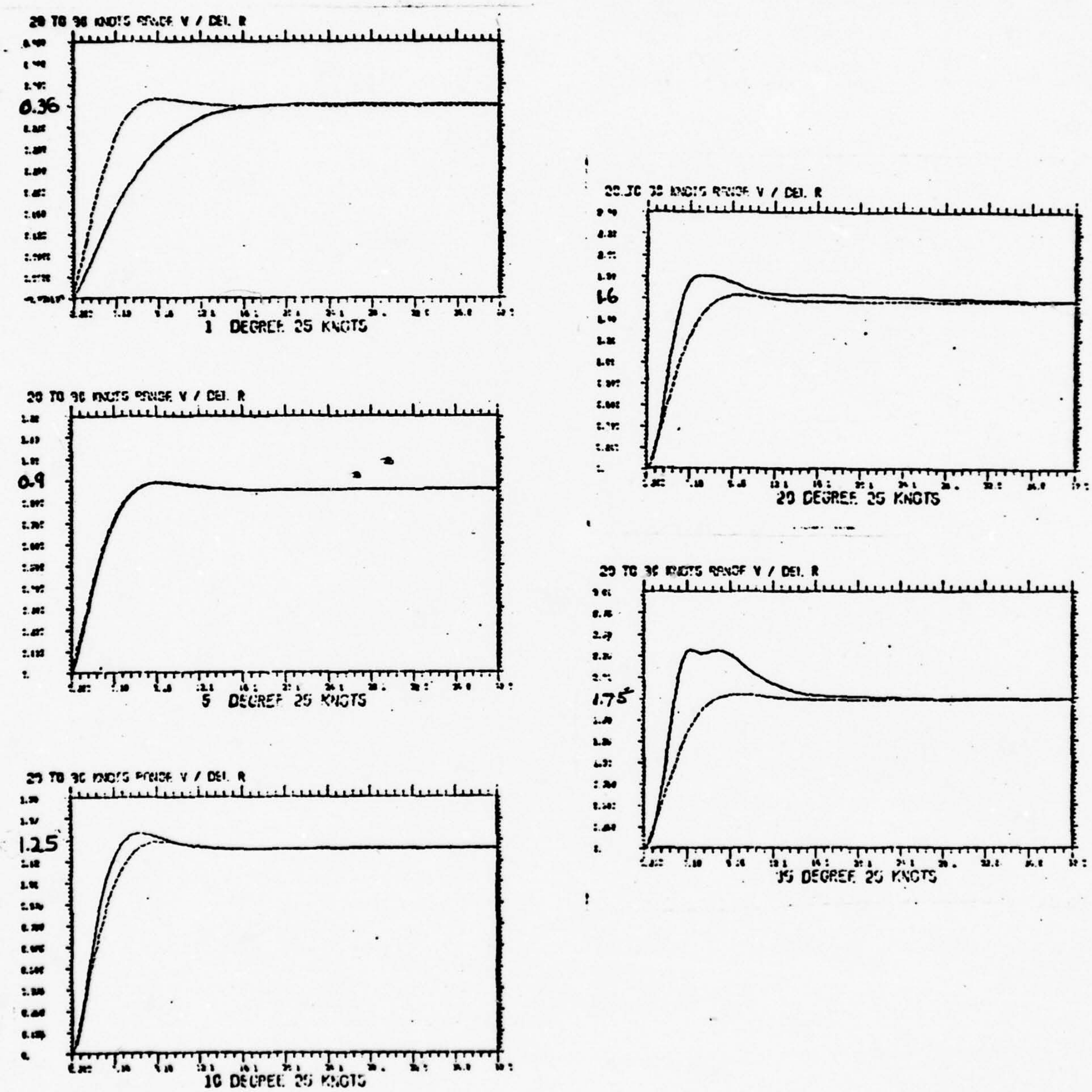


Fig. 12. V Versus δ_r, 25 Knots

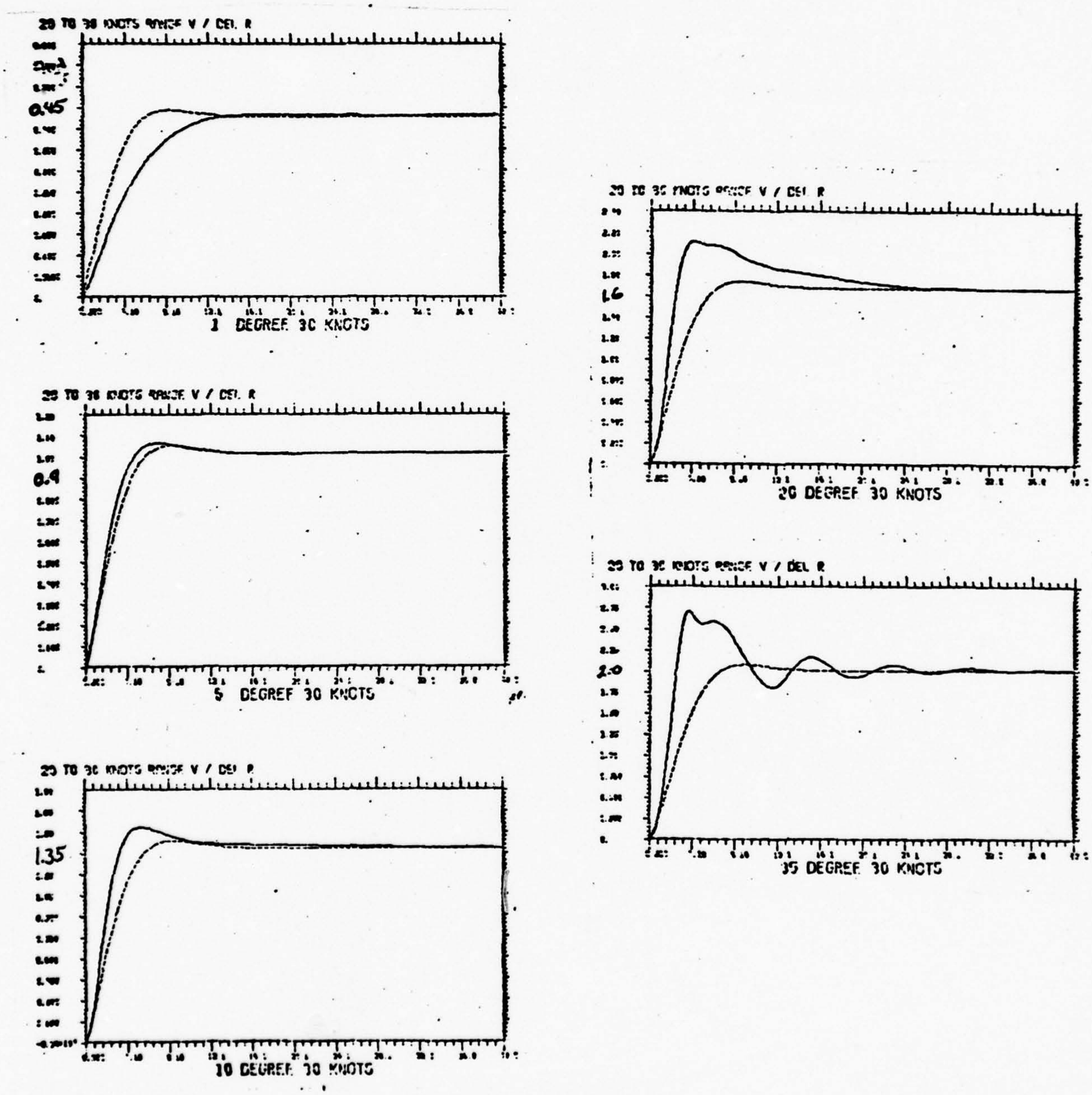
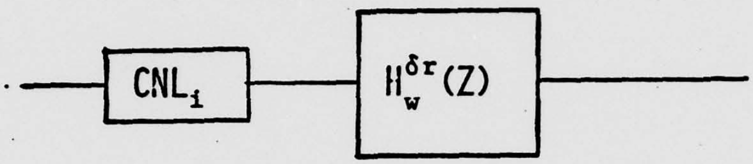


Fig. 13. V Versus δ_r, 30 Knots

Results of Validation Tests For: USF RPV

Transfer Function: W/δr

Model:



U_o: 7.5 Knots

U_-: 5 Knots

U_+: 10 Knots

$H_w^{\delta r}(Z)$ Determined Using U_o and 5° δr Step

$$H_w^{\delta r} = \frac{-2.562 \times 10^{-3} Z + 2.707 \times 10^{-3}}{Z^2 - 2.002Z + 1.003}$$

Poles in the s Domain*

$$7.071 \times 10^{-3} \pm j\, 9.211 \times 10^{-1}$$

*For conversion from Z-domain to S-domain, see references [11],[8].

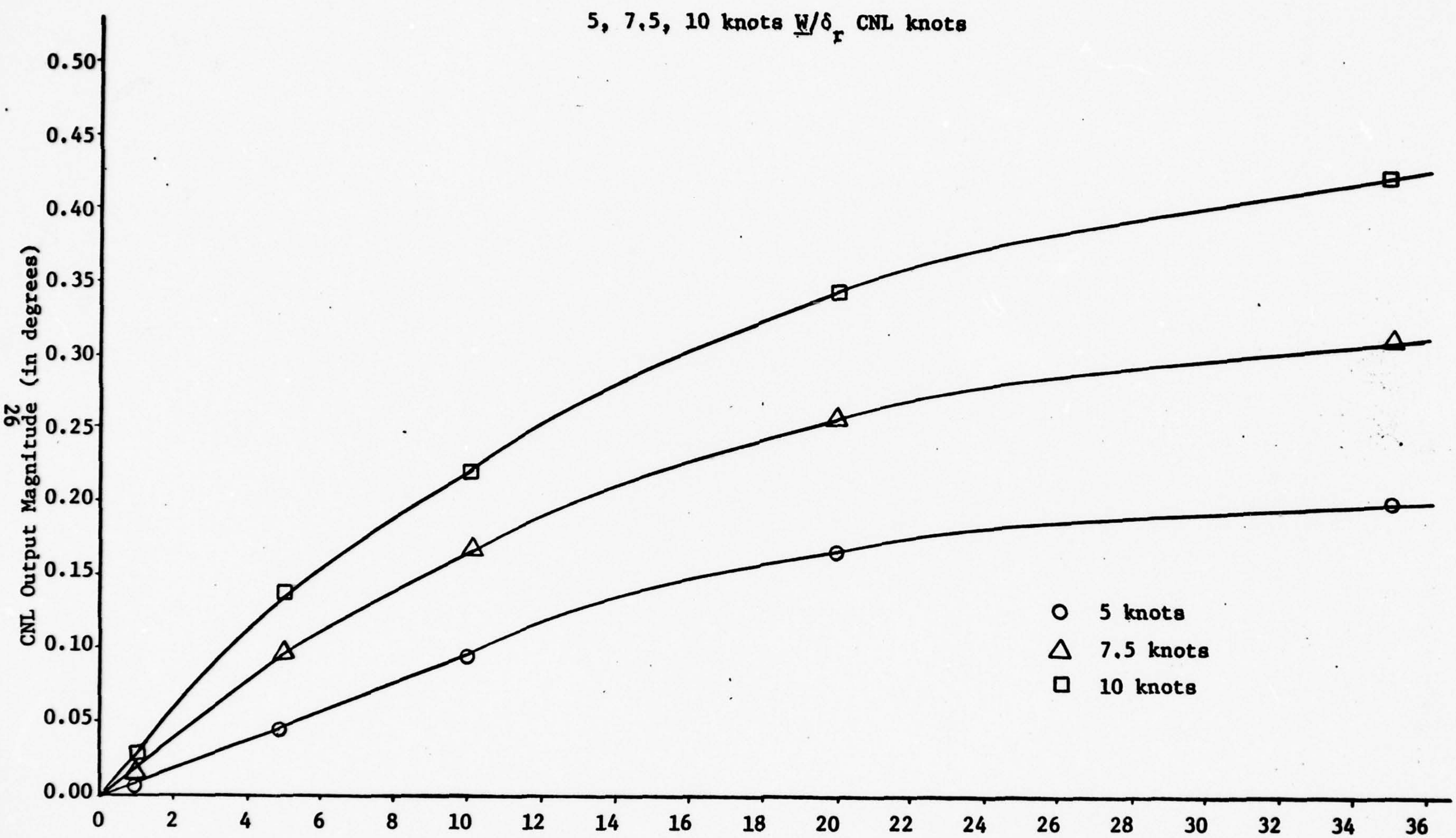

5, 7.5, 10 knots $\underline{W}/\delta_r$ CNL knots
CNL Output Magnitude (in degrees)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
5 knots
7.5 knots
10 knots

Table 7

Custom nonlinearity (CNL): w versus δ_r

5-10 knot range

δ_r Degree	w steady state 5 knots	7.5 knots	10 knots
0	0.000	0.000	0.000
1	0.004	0.013	0.026
2	0.015	0.035	0.057
3	0.023	0.054	0.060
4	0.035	0.073	0.112
5	0.043	0.096	0.135
6	0.057	0.113	0.156
7	0.067	0.127	0.175
8	0.076	0.142	0.190
9	0.086	0.155	0.207
10	0.094	0.166	0.219
11	0.105	0.176	0.235
12	0.115	0.183	0.249
13	0.122	0.195	0.262
14	0.130	0.206	0.275
15	0.137	0.215	0.290
16	0.145	0.223	0.302
17	0.150	0.231	0.313
18	0.157	0.240	0.323
19	0.162	0.247	0.333
20	0.165	0.257	0.340
21	0.170	0.264	0.349
22	0.172	0.267	0.355
23	0.175	0.273	0.361
24	0.177	0.277	0.367
25	0.180	0.281	0.373
26	0.183	0.285	0.377
27	0.185	0.288	0.383
28	0.187	0.290	0.387
29	0.189	0.294	0.393
30	0.191	0.296	0.398
31	0.193	0.300	0.402
32	0.195	0.303	0.406
33	0.197	0.305	0.412
34	0.198	0.306	0.415
35	0.203	0.307	0.420
36	0.203	0.310	0.423

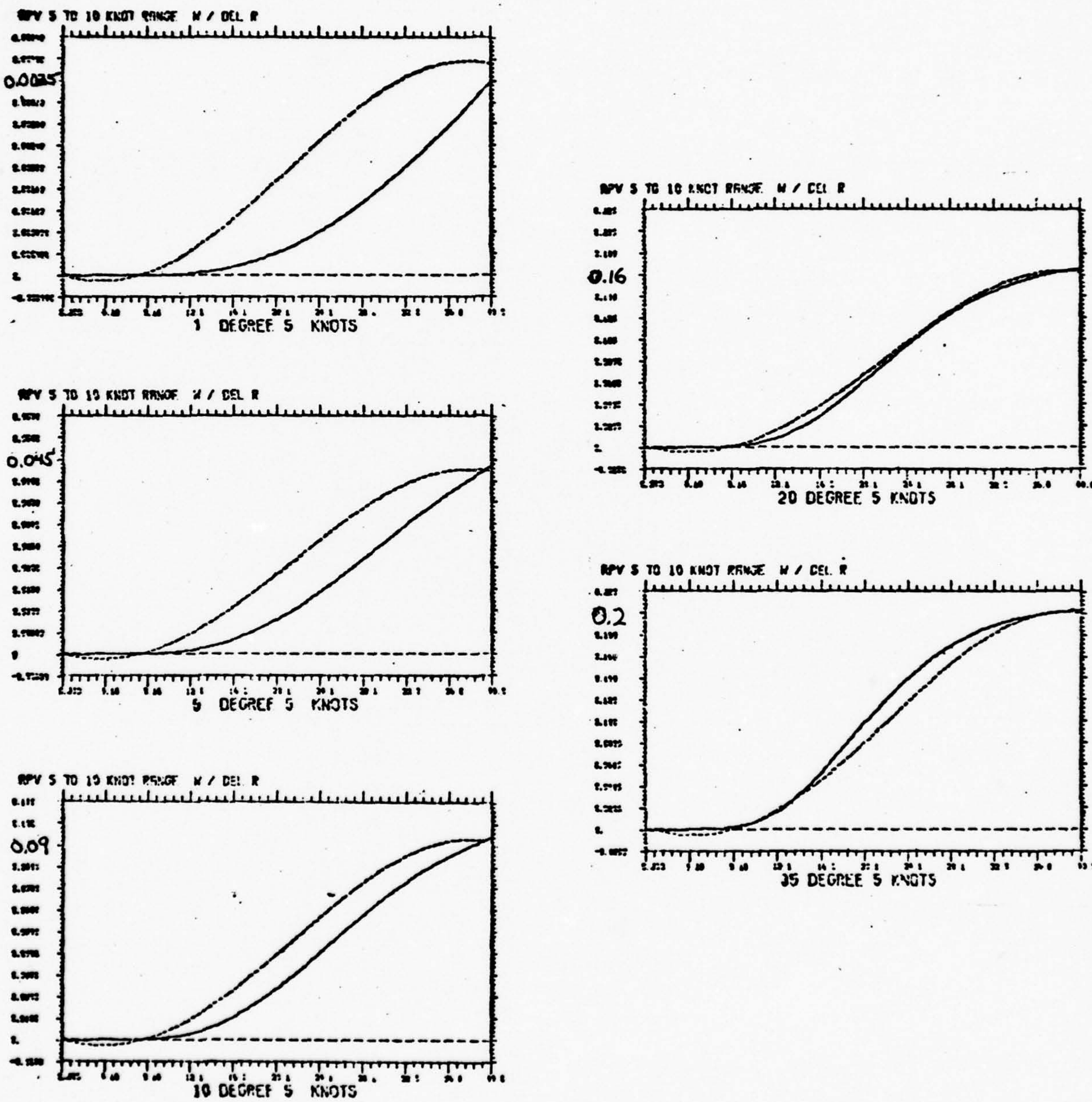


Fig. 15. W Versus δ_r, 5 Knots

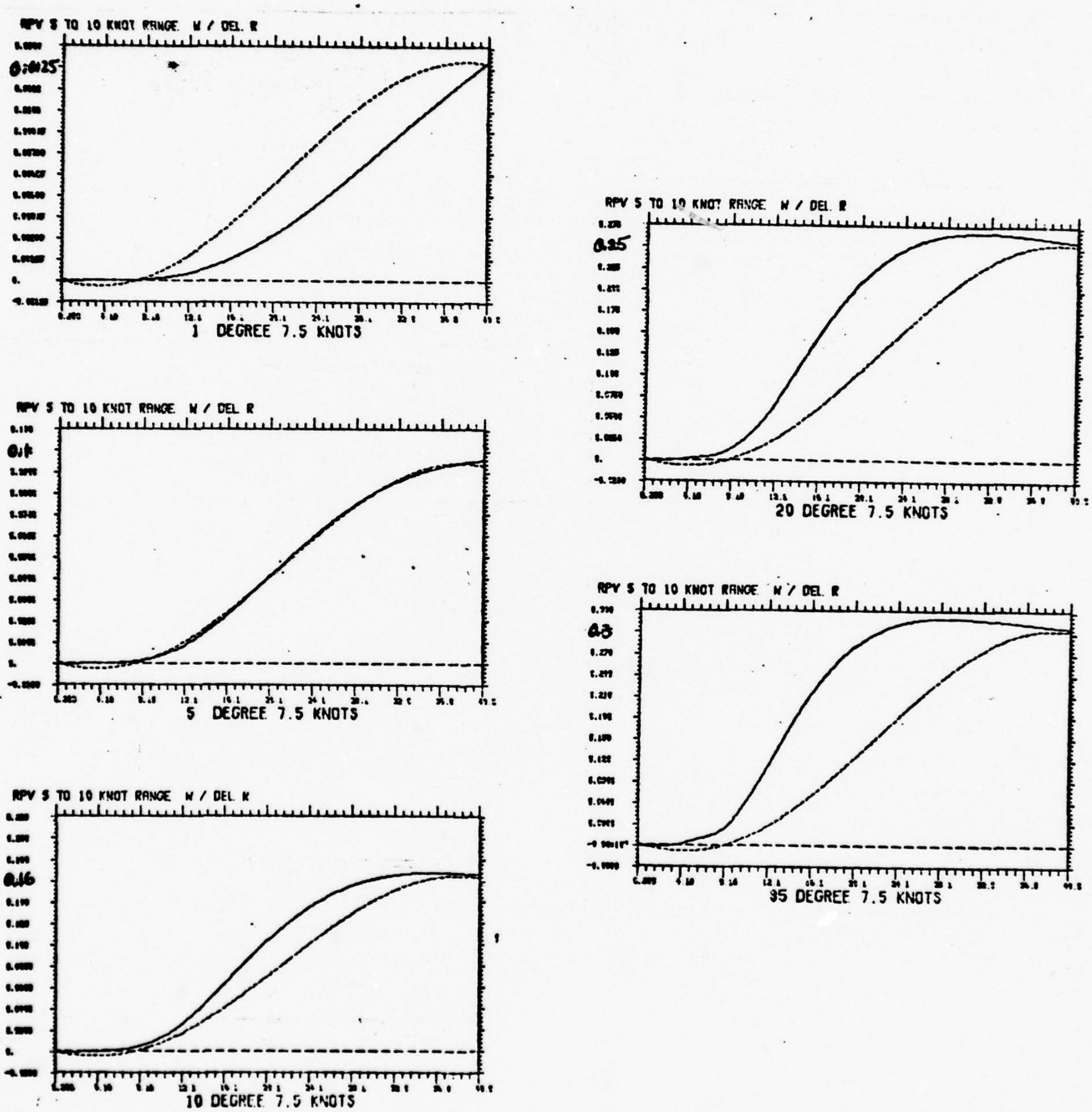


Fig. 16. W Versus δ_r, 7.5 Knots

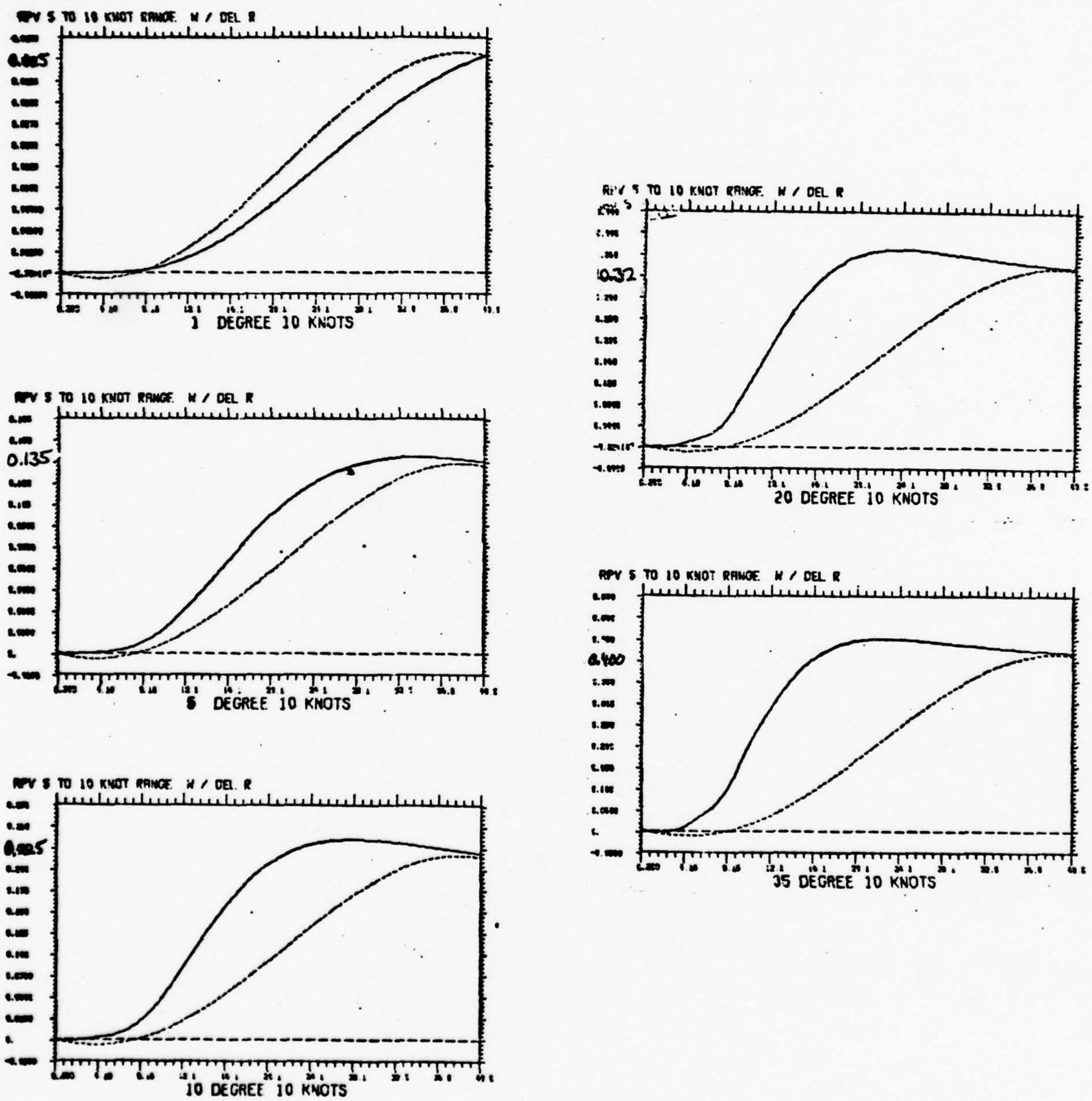
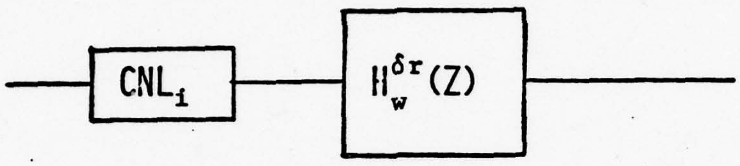


Fig. 17. W Versus δ_r, 10 Knots

RESULTS OF VALIDATION TESTS FOR: USF RPV

TRANSFER FUNCTION: $w/\delta r$

MODEL:



U_o: 15 Knots

U_-: 10 Knots

U_+: 20 Knots

$H_w^{\delta r}(Z)$ DETERMINED USING U_o AND 5° δr STEP

$$H_w^{\delta r} = \frac{-1.046 \times 10^{-2} Z + 1.146 \times 10^{-2}}{Z^2 - 1.966Z + 9.667 \times 10^{-1}}$$

POLES IN THE s DOMAIN*

$$-8.460 \times 10^{-2} \pm j\, 1.356 \times 10^{-1}$$

*For conversion from Z-domain to S-domain, see references [11],[8].

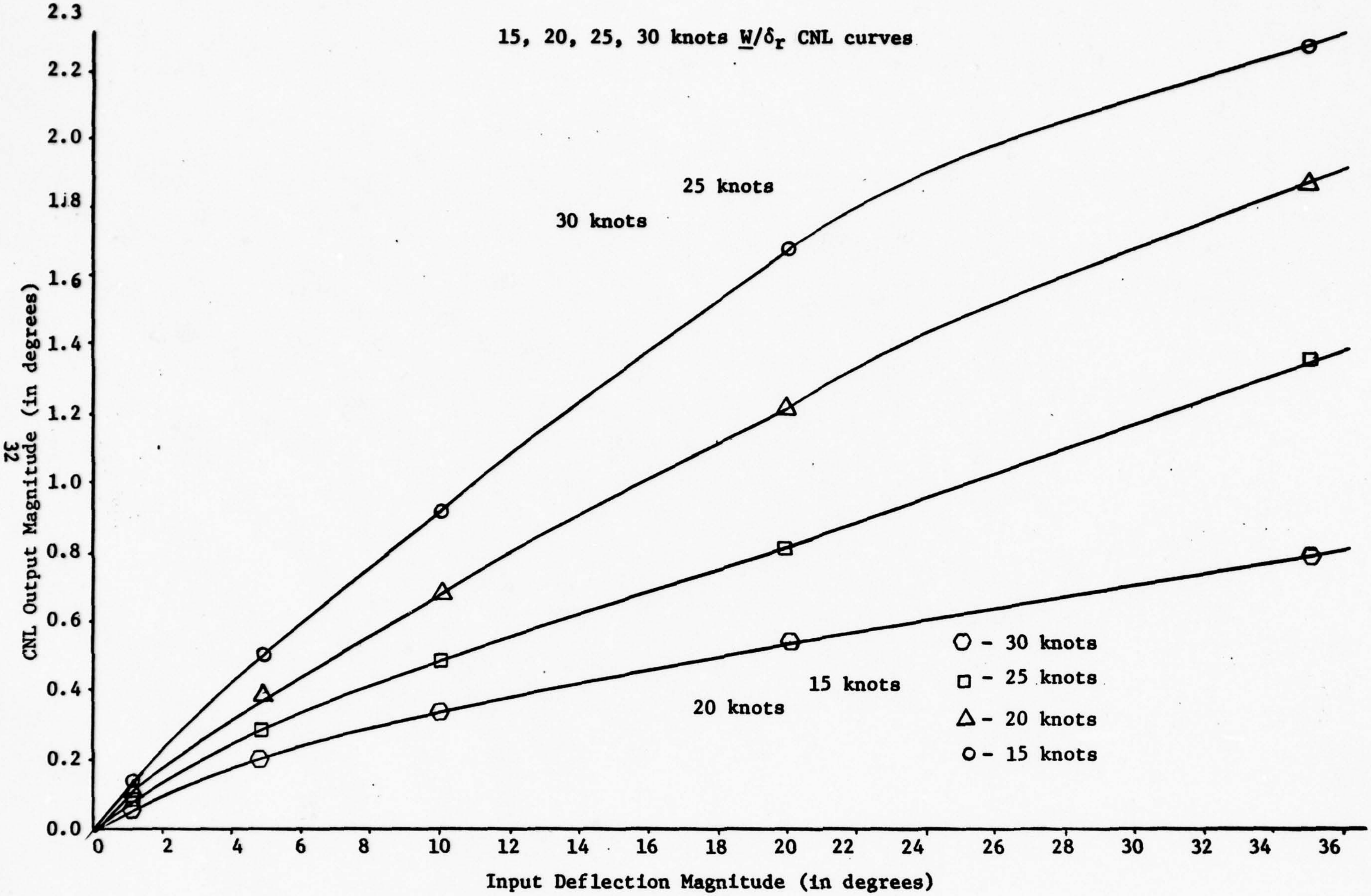

15, 20, 25, 30 knots $\underline{W}/\delta_r$ CNL curves
25 knots
30 knots
15 knots
20 knots
⬡ - 30 knots
□ - 25 knots
△ - 20 knots
○ - 15 knots
CNL Output Magnitude (in degrees)
2.3
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
Input Deflection Magnitude (in degrees)

Fig. 18

Table 8

Custom nonlinearity (CNL): W versus δ_r

10-20 knot range

δ_r	W steady state		
Degree	10 knots	15 knots	20 knots
0	0.000	0.00	0.00
1	0.026	0.05	0.07
2	0.057	0.09	0.13
3	0.060	0.13	0.19
4	0.112	0.17	0.23
5	0.135	0.20	0.28
6	0.156	0.23	0.32
7	0.175	0.26	0.37
8	0.190	0.28	0.40
9	0.207	0.31	0.44
10	0.219	0.33	0.48
11	0.235	0.35	0.52
12	0.249	0.37	0.55
13	0.262	0.39	0.58
14	0.275	0.41	0.61
15	0.290	0.43	0.65
16	0.302	0.45	0.68
17	0.313	0.47	0.71
18	0.323	0.49	0.74
19	0.333	0.51	0.78
20	0.340	0.53	0.81
21	0.349	0.54	0.85
22	0.355	0.56	0.88
23	0.361	0.58	0.92
24	0.367	0.60	0.96
25	0.373	0.62	0.99
26	0.377	0.63	1.03
27	0.383	0.65	1.06
28	0.387	0.67	1.10
29	0.393	0.68	1.14
30	0.398	0.70	1.18
31	0.402	0.72	1.21
32	0.406	0.74	1.24
33	0.412	0.76	1.28
34	0.415	0.77	1.32
35	0.420	0.79	1.35
36	0.423	0.80	1.38

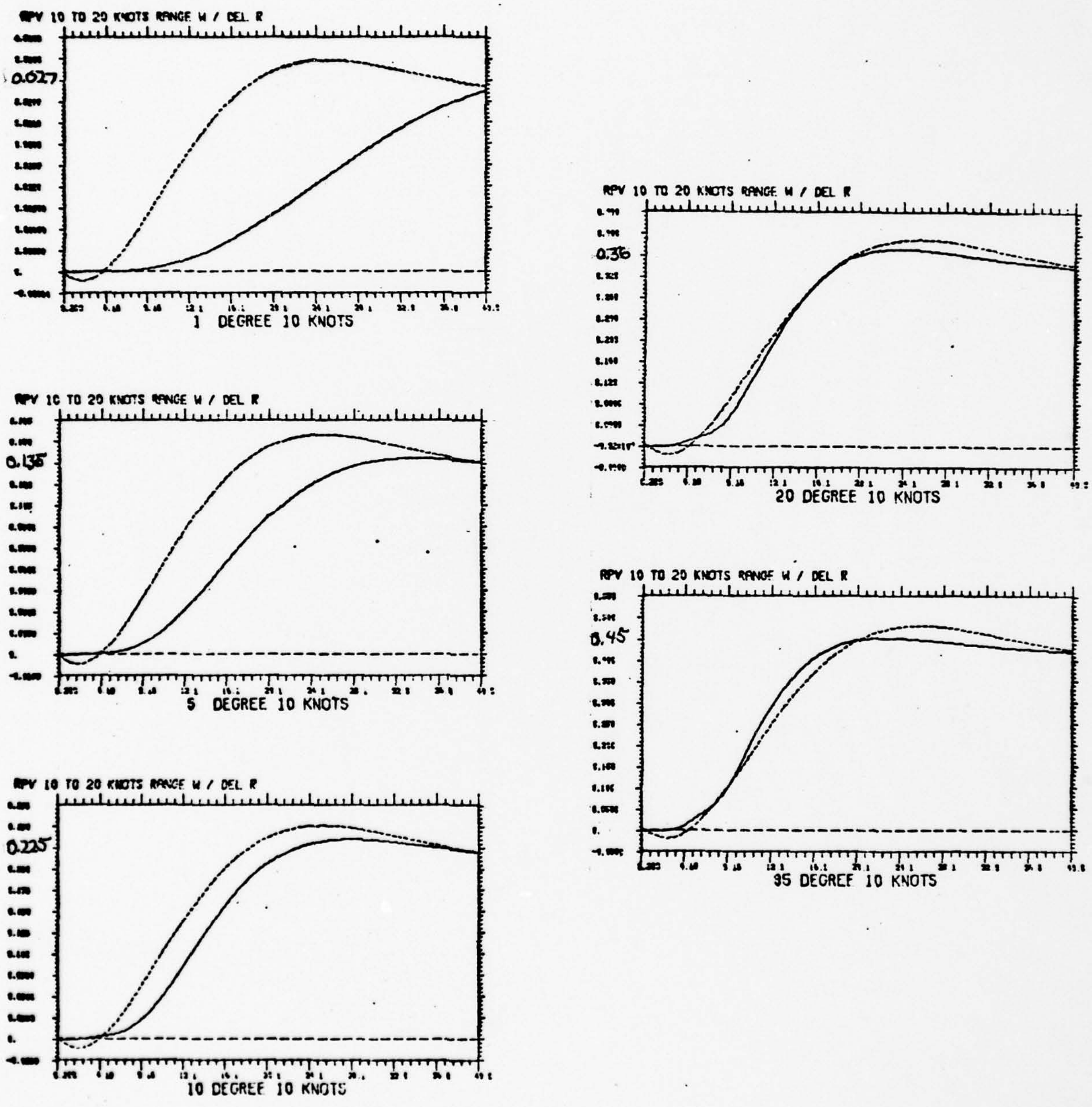


Fig. 19. W Versus δ_r, 10 Knots

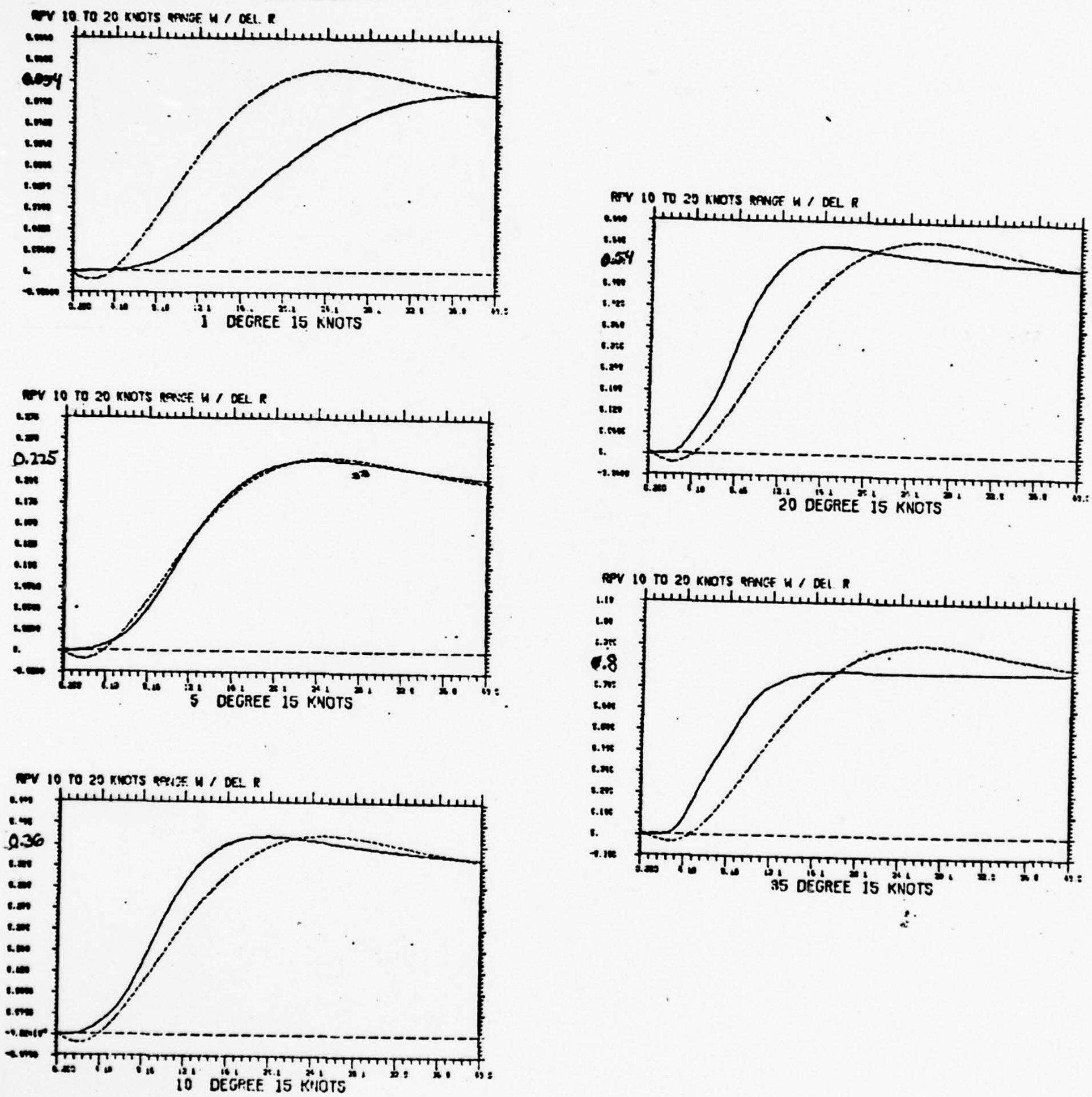


Fig. 20. W Versus δ_r, 15 Knots

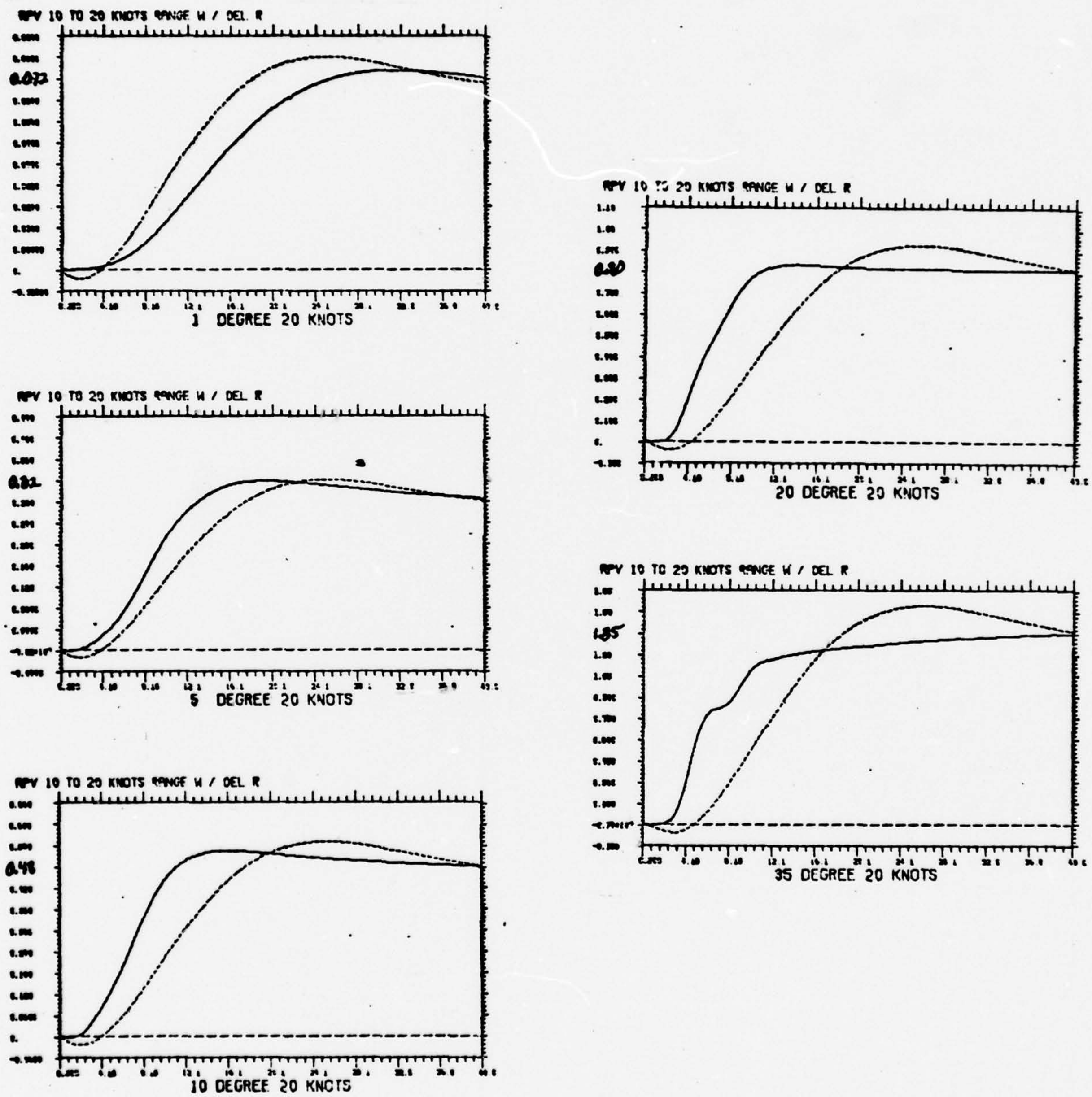
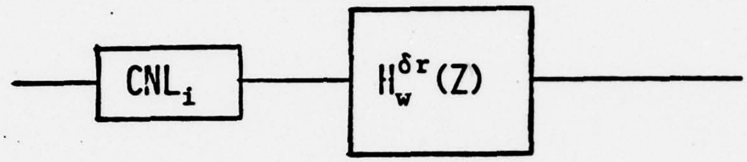


Fig. 21. W Versus δ_r, 20 Knots

Results of Validation Tests For: USF RPV

Transfer Function: $w/\delta r$

Model:



U_o: 25 Knots

U_-: 20 Knots

U_+: 30 Knots

$H_w^{\delta r}(Z)$ Determined Using U_o and 5° δr Step

$$H_w^{\delta r} = \frac{-1.191 \times 10^{-2} Z + 1.467 \times 10^{-2}}{Z^2 - 1.931Z + 9.337 \times 10^{-1}}$$

Poles in the s Domain*

$$-1.716 \times 10^{-1} \pm j\, 1.992 \times 10^{-1}$$

*For conversion from Z-domain to S-domain, see references [11],[8].

TABLE 9

Custom Nonlinearity (CNL): W Versus δ_r

20-35 Knot Range

δ_r Degree	R Steady State 20 knots	25 knots	30 knots
0	0.00	0.00	0.00
1	0.07	0.09	0.12
2	0.13	0.17	0.22
3	0.19	0.24	0.33
4	0.23	0.32	0.42
5	0.28	0.38	0.51
6	0.32	0.44	0.59
7	0.37	0.50	0.67
8	0.40	0.56	0.76
9	0.44	0.62	0.84
10	0.48	0.67	0.91
11	0.52	0.73	1.00
12	0.55	0.79	1.08
13	0.58	0.84	1.16
14	0.61	0.90	1.23
15	0.65	0.95	1.31
16	0.68	1.00	1.38
17	0.71	1.06	1.46
18	0.74	1.11	1.53
19	0.78	1.16	1.60
20	0.81	1.21	1.67
21	0.85	1.26	1.74
22	0.88	1.31	1.80
23	0.92	1.36	1.85
24	0.96	1.40	1.90
25	0.99	1.44	1.94
26	1.03	1.49	1.98
27	1.06	1.54	2.02
28	1.10	1.58	2.06
29	1.14	1.62	2.09
30	1.18	1.67	2.12
31	1.21	1.71	2.15
32	1.24	1.75	2.18
33	1.28	1.79	2.22
34	1.32	1.83	2.25
35	1.35	1.86	2.27
36	1.38	1.90	2.29

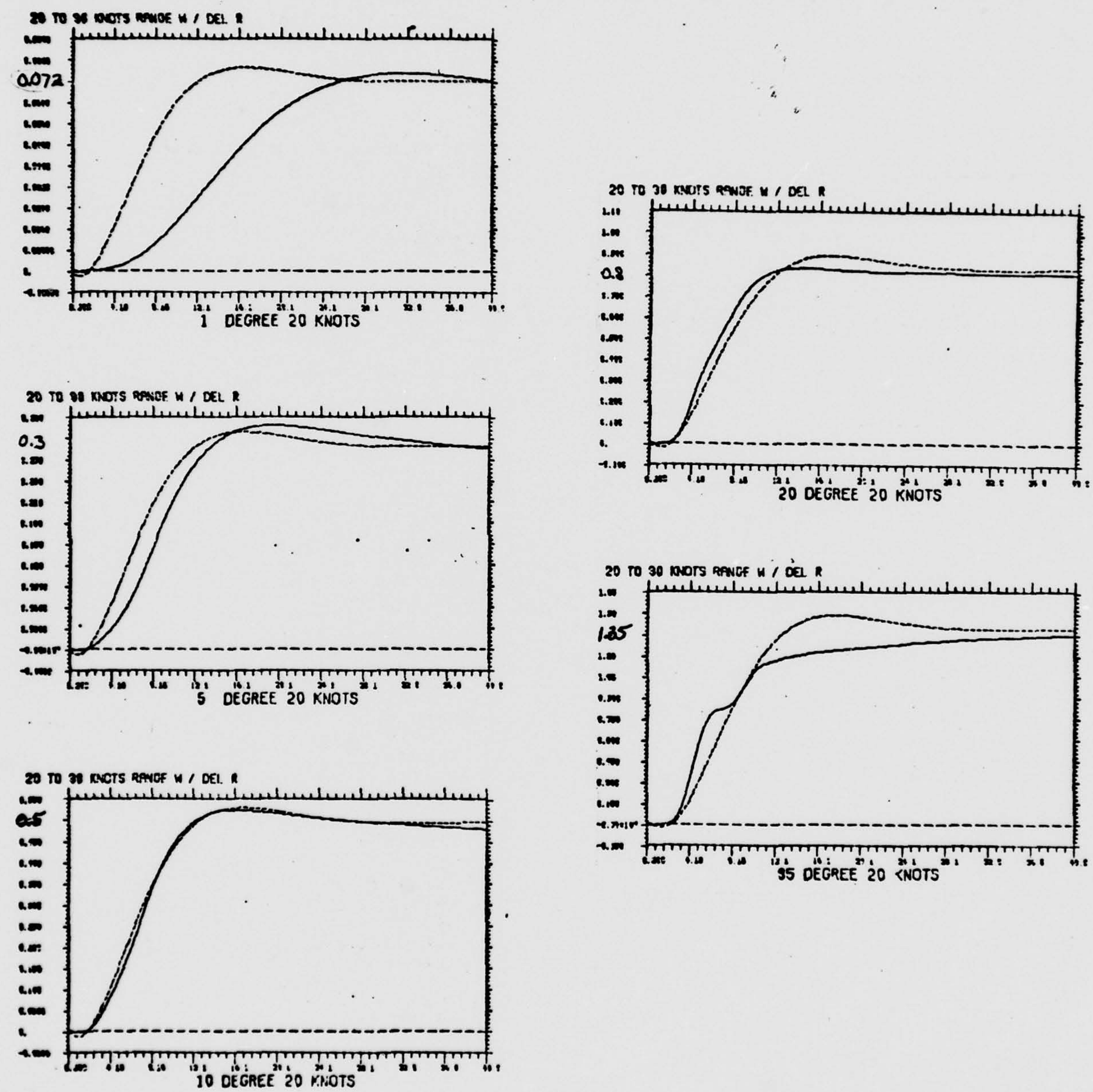


Fig. 22. W Versus δ_r, 20 Knots

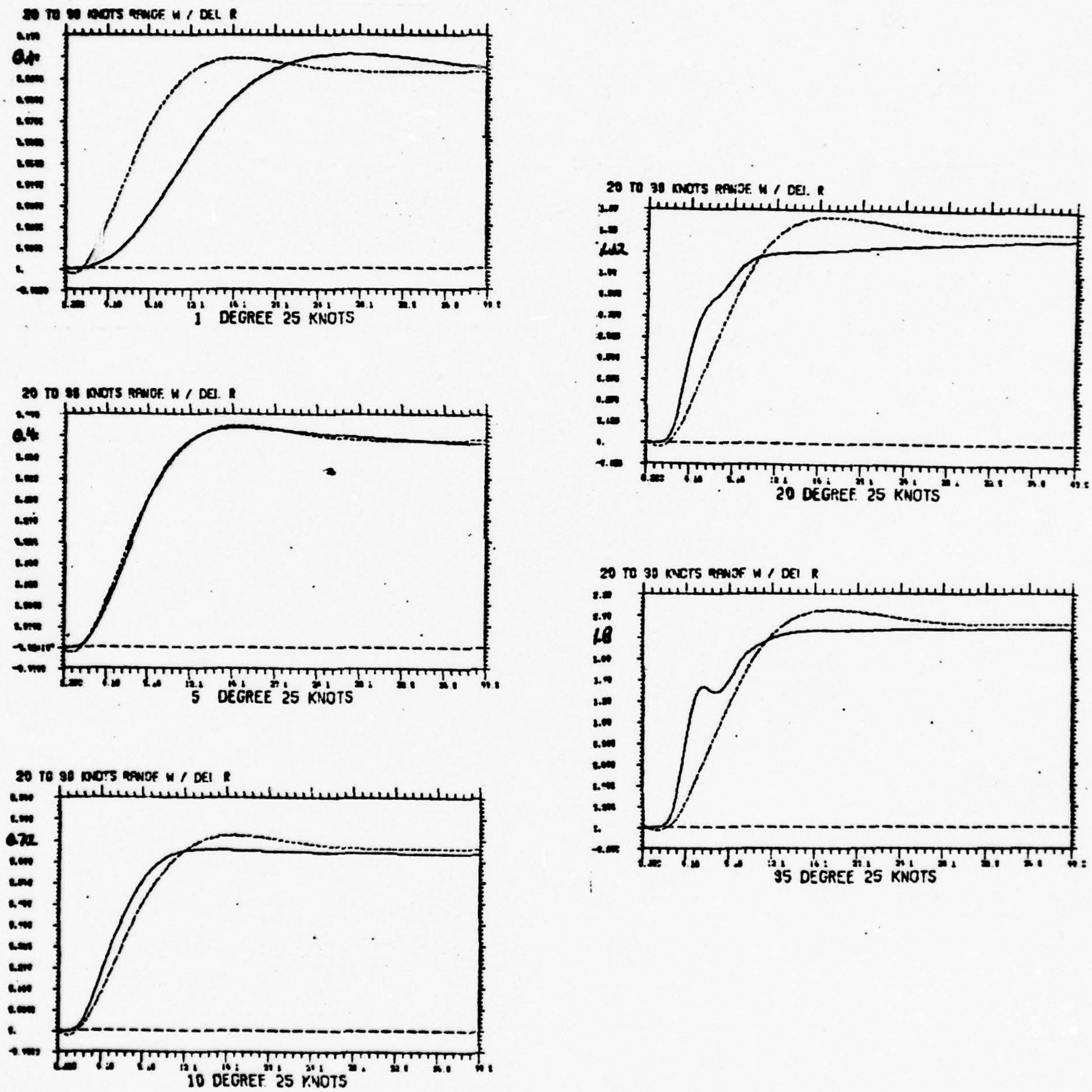


Fig. 23. W Versus δ_r, 25 Knots

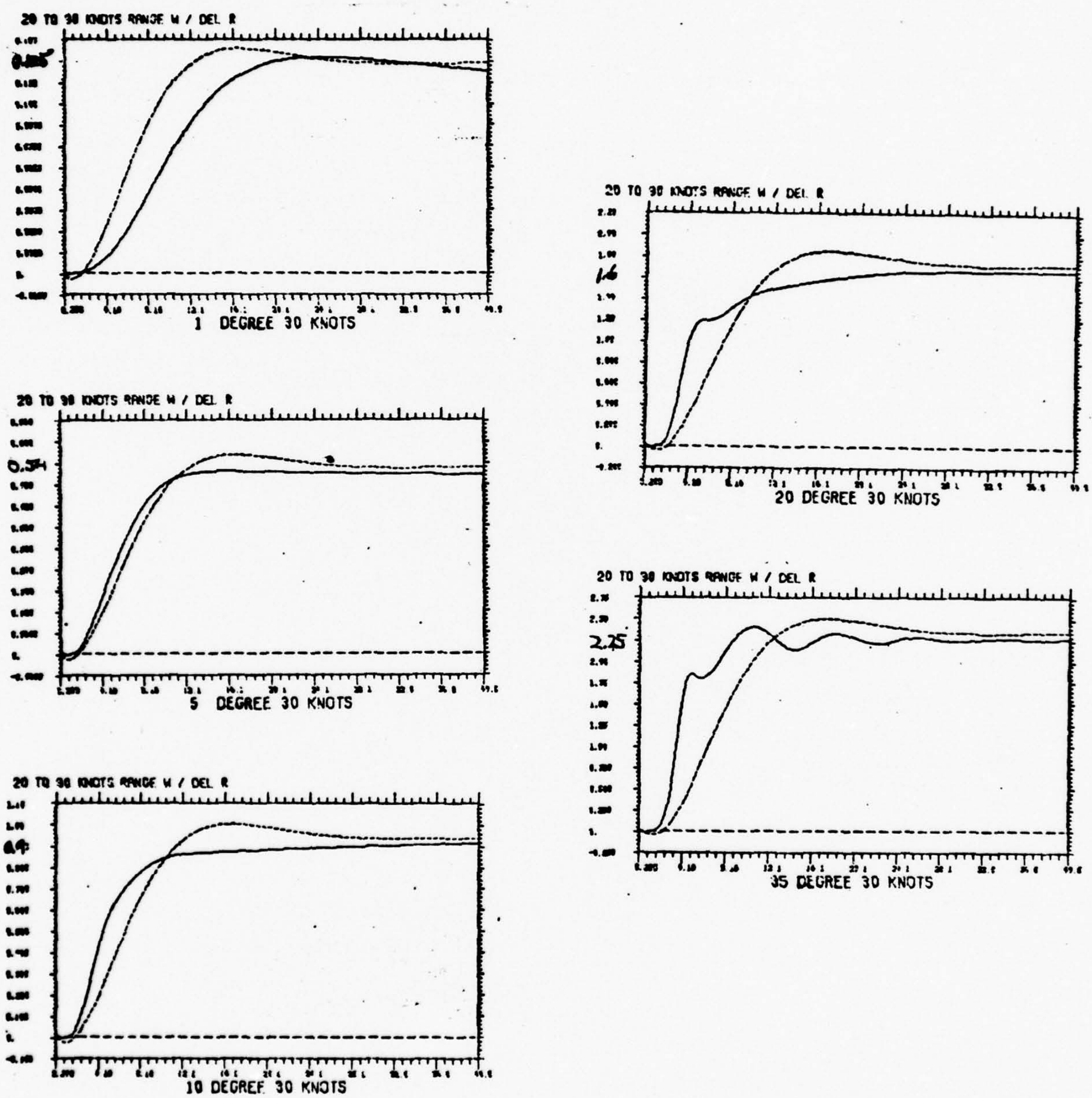
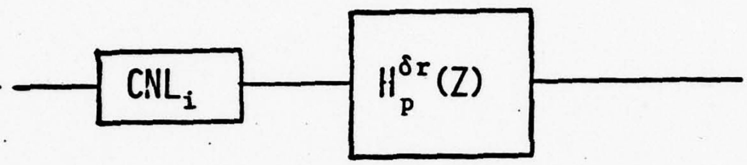


Fig. 24. W Versus δ_r, 30 Knots

RESULTS OF VALIDATION TESTS FOR: USF RPV

TRANSFER FUNCTION: $P/\delta r$

MODEL:



U_o: 7.5 Knots

U_-: 5 Knots

U_+: 10 Knots

$H_p^{\delta r}(Z)$ DETERMINED USING U_o AND 5° δr STEP

$$H^{\delta r} = \frac{-2.633 \times 10^{-1}Z^3 + 8.342 \times 10^{-1}Z^2 - 8.796 \times 10^{-1}Z + 3.086 \times 10^{-1}}{Z^4 - 3.837Z^3 + 5.589Z^2 - 3.669Z + 9.165 \times 10^{-1}}$$

POLES IN THE S DOMAIN*

$4.3 \times 10^{-2} \pm j\, 5.411 \times 10^{-2}$

*For conversion from Z-domain to S-domain, see references [11],[8].

Table 10

Custom nonlinearity (CNL): P versus δ_r

5-10 knot range

δ_r	P steady state		
Degree	5 knots	7.5 knots	10 knots
0	0.00	0.0	0.0
1	-0.01	-0.03	-0.07
2	-0.02	-0.06	-0.13
3	-0.03	-0.09	-0.19
4	-0.045	-0.12	-0.25
5	-0.06	-0.16	-0.31
6	-0.072	-0.20	-0.37
7	-0.084	-0.23	-0.43
8	-0.096	-0.25	-0.49
9	-0.108	-0.28	-0.54
10	-0.120	-0.30	-0.59
11	-0.129	-0.33	-0.64
12	-0.138	-0.36	-0.68
13	-0.147	-0.38	-0.72
14	-0.156	-0.40	-0.76
15	-0.165	-0.42	-0.81
16	-0.174	-0.44	-0.86
17	-0.183	-0.46	-0.90
18	-0.193	-0.48	-0.95
19	-0.201	-0.50	-0.99
20	-0.210	-0.52	-1.04
21	-0.217	-0.54	-1.07
22	-0.224	-0.56	-1.10
23	-0.231	-0.57	-1.13
24	-0.236	-0.58	-1.16
25	-0.240	-0.60	-1.19
26	-0.243	-0.61	-1.22
27	-0.246	-0.62	-1.25
28	-0.249	-0.63	-1.28
29	-0.252	-0.64	-1.31
30	-0.255	-0.65	-1.33
31	-0.258	-0.66	-1.35
32	-0.261	-0.67	-1.37
33	-0.264	-0.68	-1.39
34	-0.267	-0.70	-1.41
35	-0.270	-0.71	-1.42
36	-0.273		-1.44

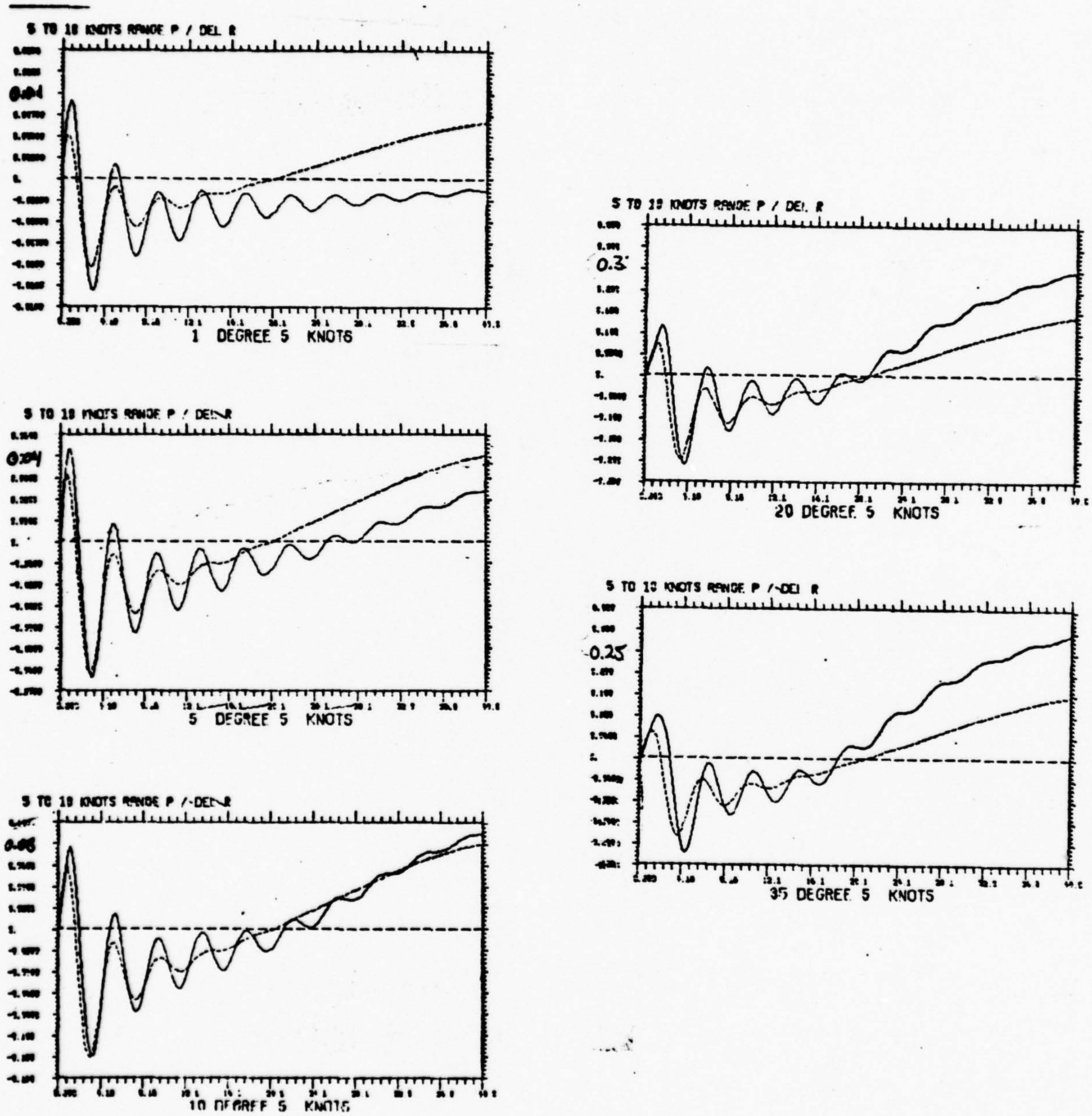


Fig. 25. P Versus δ_r, 5 Knots

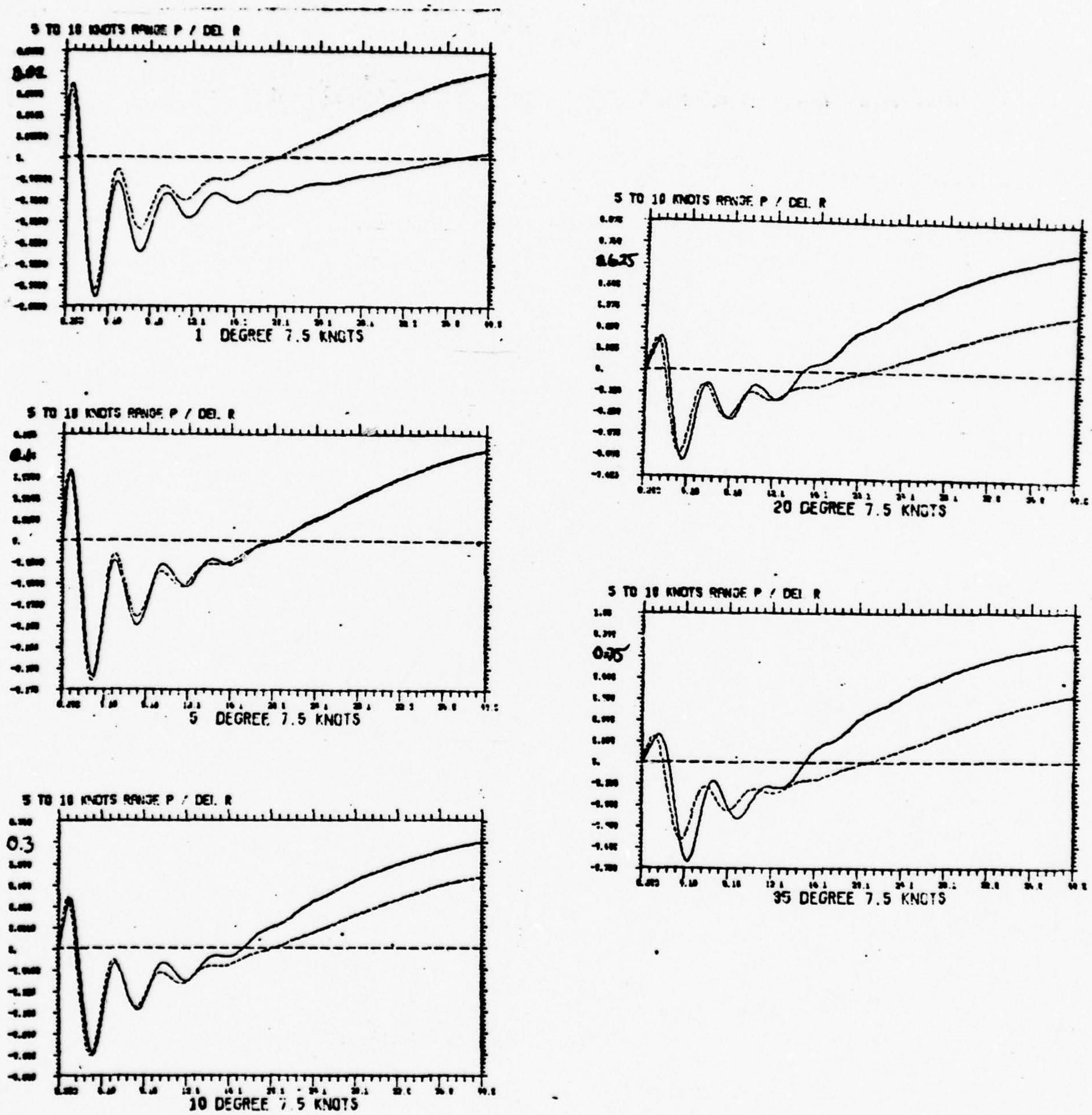


Fig. 26. P Versus δ_r, 7.5 Knots

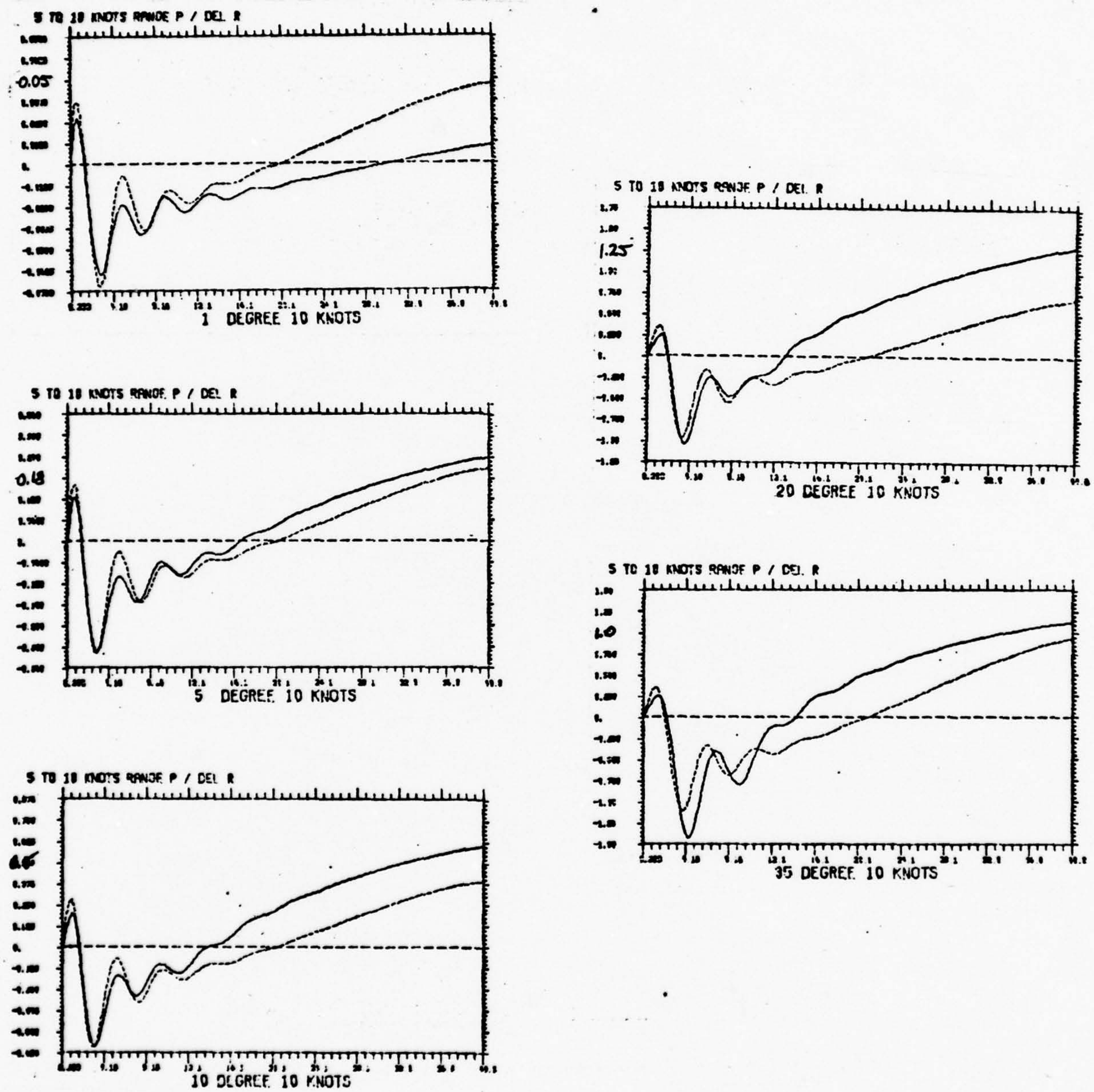
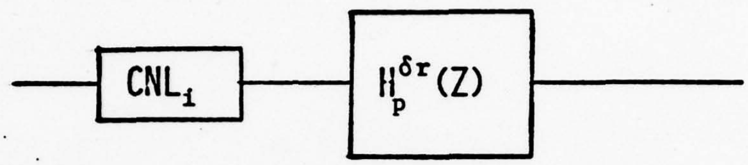


Fig. 27. P Versus δ_r, 10 Knots

Results of Validation Tests For: USF RPV

Transfer Function: $p/\delta r$

Model:



U_o: 15 Knots

U_-: 10 Knots

U_+: 20 Knots

$H_p^{\delta r}(Z)$ Determined Using U_o and 5° δr Step

$$H^{\delta r} = \frac{-1.604 \times 10^{-1} Z^3 + 6.043 \times 10^{-1} Z^2 - 6.702 \times 10^{-1} + 2.464 \times 10^{-1}}{Z^4 - 3.771Z^3 + 5.370Z^2 - 3.430Z + 8.305 \times 10^{-1}}$$

Poles in the s Domain*

1.99×10^{-1}

-5.9985×10^{-2}

$-5.34 \times 10^{-1} \pm j\, 1.244$

*For conversion from Z-domain to S-domain, see references [11],[8].

Table 11

Custom nonlinearity (CNL): P versus δ_r

10-20 knot range

δ_r	P steady state		
Degree	10 knots	15 knots	20 knots
0	0.0	0.00	0.00
1	-0.07	-0.18	-0.38
2	-0.13	-0.34	-0.70
3	-0.19	-0.51	-1.05
4	-0.25	-0.68	-1.38
5	-0.31	-0.85	-1.76
6	-0.37	-1.00	-2.06
7	-0.43	-1.13	-2.34
8	-0.49	-1.28	-2.66
9	-0.54	-1.42	-2.98
10	-0.59	-1.58	-3.25
11	-0.64	-1.71	-3.55
12	-0.68	-1.84	-3.80
13	-0.72	-1.96	-4.08
14	-0.76	-2.08	-4.36
15	-0.81	-2.20	-4.62
16	-0.86	-2.33	-4.90
17	-0.90	-2.46	-5.18
18	-0.95	-2.58	-5.42
19	-0.99	-2.70	-5.70
20	-1.04	-2.83	-5.99
21	-1.07	-2.93	-6.26
22	-1.10	-3.02	-6.54
23	-1.13	-3.12	-6.82
24	-1.16	-3.21	-7.10
25	-1.19	-3.30	-7.40
26	-1.22	-3.40	-7.68
27	-1.25	-3.50	-7.96
28	-1.28	-3.59	-8.24
29	-1.31	-3.69	-8.52
30	-1.33	-3.78	-8.80
31	-1.35	-3.87	-9.10
32	-1.37	-3.96	-9.40
33	-1.39	-4.05	-9.66
34	-1.41	-4.15	-9.95
35	-1.42	-4.25	-10.24
36	-1.44	-4.34	-10.52

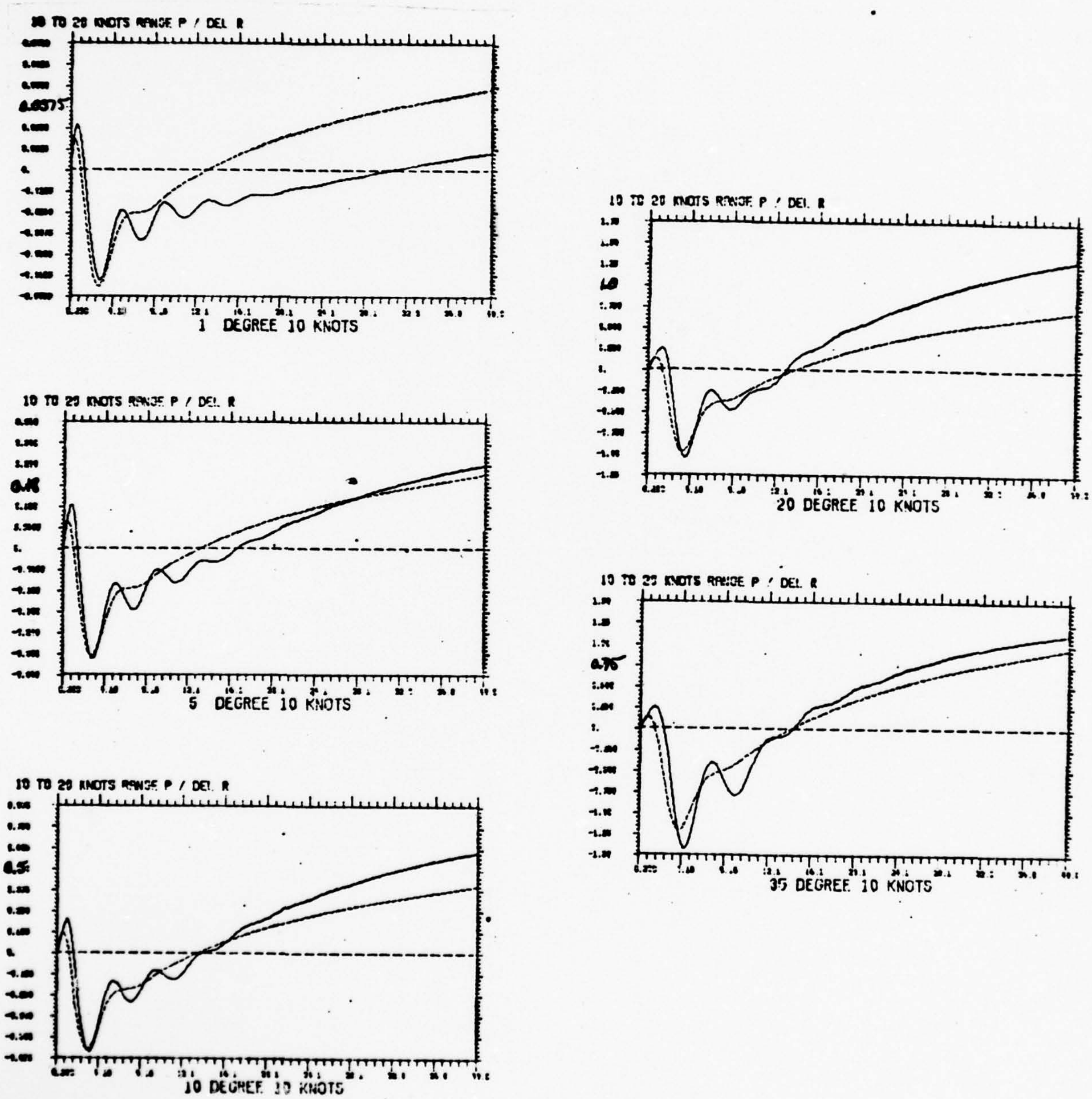


Fig. 28. P Versus δ_r, 10 Knots

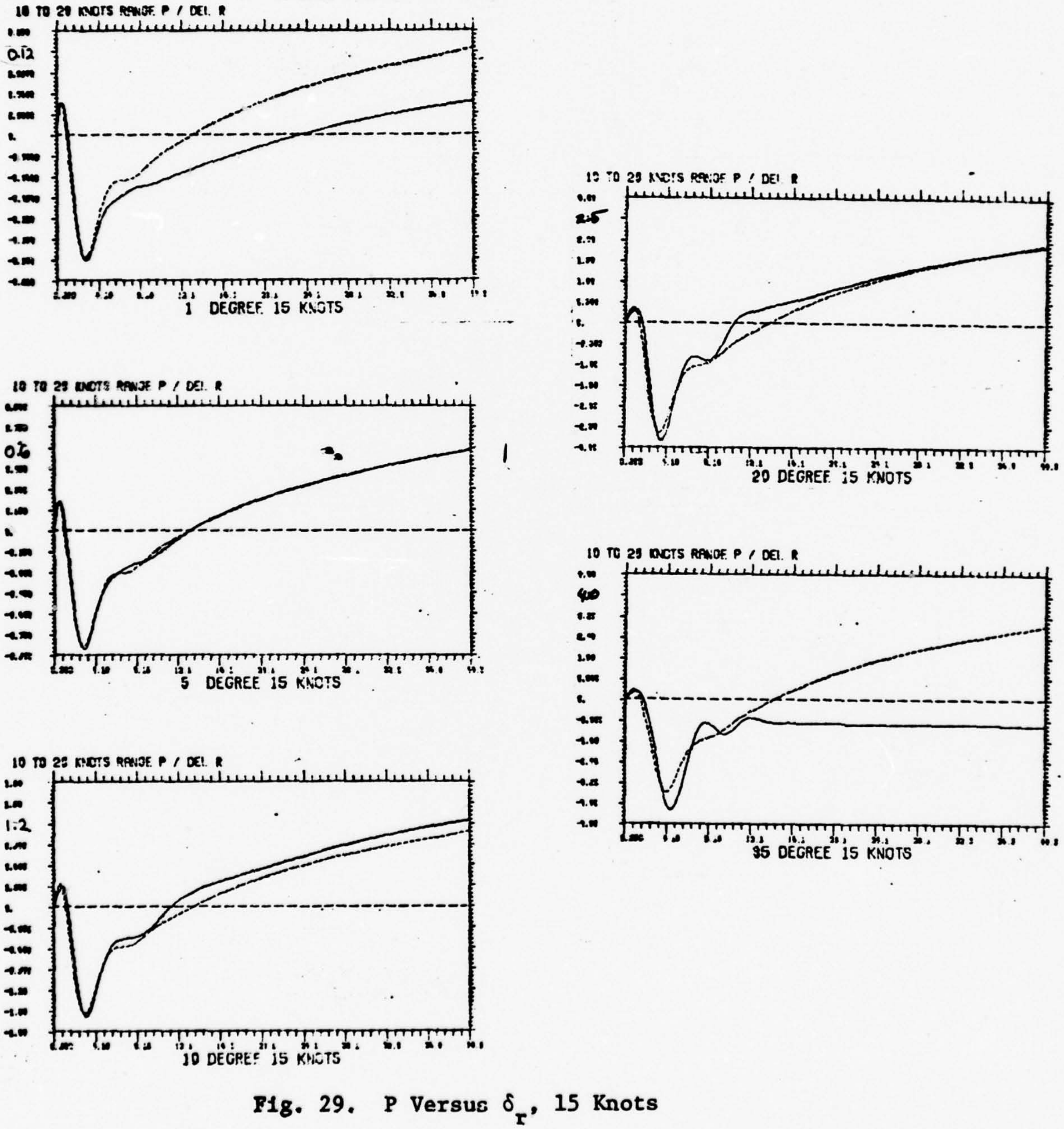


Fig. 29. P Versus δ_r, 15 Knots

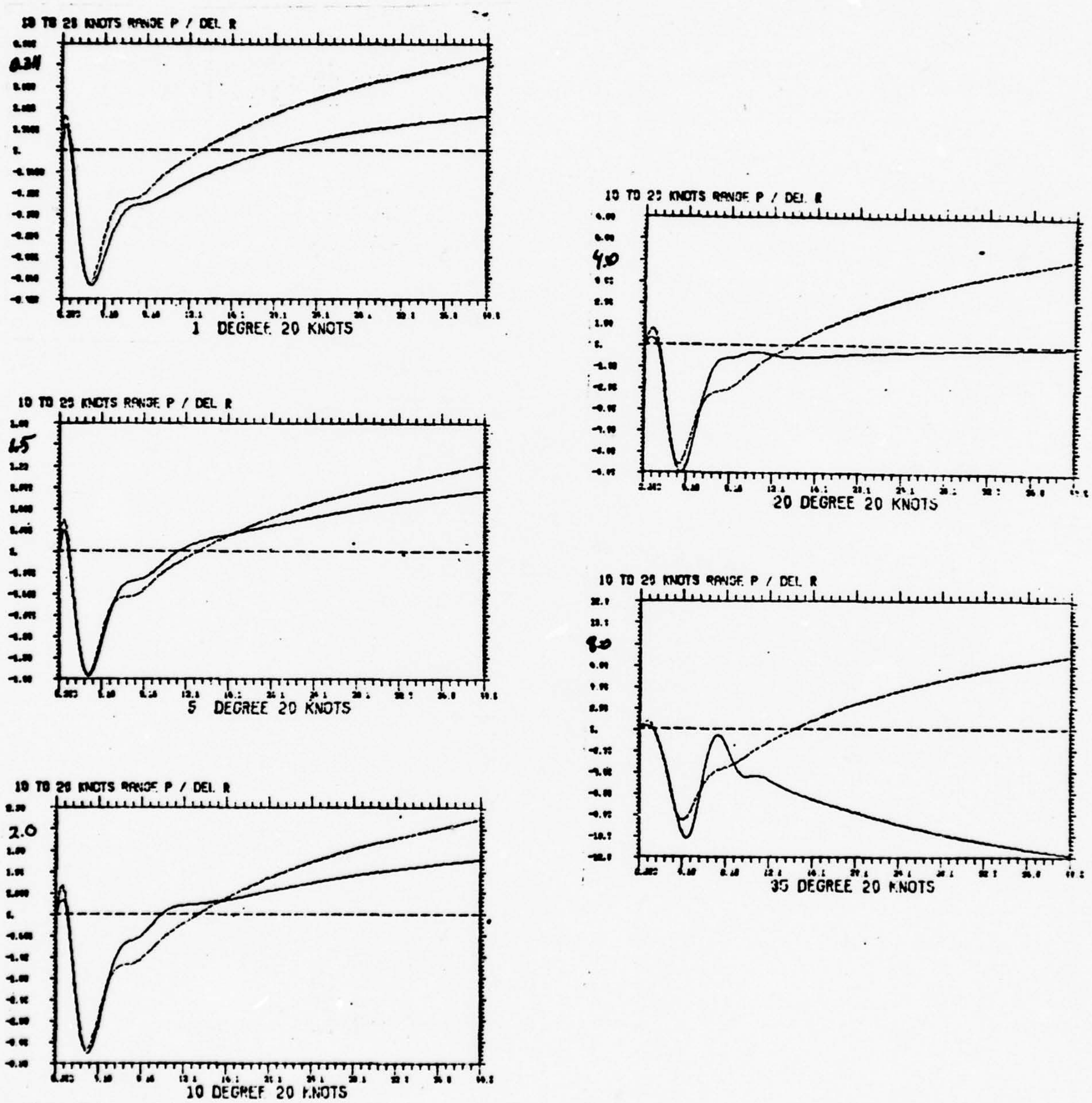
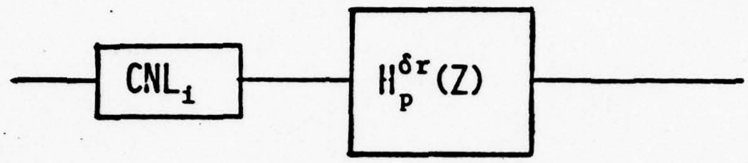


Fig.30. **P Versus δ_r, 20 Knots**

Results of Validation Tests For: USF RPV

Transfer Function: $P/\delta r$

Model:



U_o: 25 Knots

U_-: 20 Knots

U_+: 30 Knots

$H_p^{\delta r}(Z)$ Determined Using U_o and 5° δr Step

$$H^{\delta r} = \frac{-1.240 \times 10^{-1} Z^3 + 4.374 \times 10^{-1} Z^2 - 5.026 \times 10^{-1}}{Z^4 - 3.641 Z^3 + 4.993 Z^2 - 3.060 Z + 7.071 \times 10^{-1}}$$

Poles in the s Domain*

-4.699×10^{-3}

-3.665×10^{-1}

*For conversion from Z-domain to S-domain, see references [11],[8].

Table 12

Custon nonlinearity (CNL): P versus δ_r.

20-30 knot range

δ_r	P steady state		
Degree	20 knots	25 knots	30 knots
0	0.0	0.0	0.0
1	-0.38	-0.68	-1.2
2	-0.70	-1.15	-2.0
3	-1.05	-1.75	-3.1
4	-1.38	-2.40	-4.0
5	-1.76	-3.10	-4.9
6	-2.06	-3.60	-5.8
7	-2.34	-4.10	-6.7
8	-2.66	-4.60	-7.5
9	-2.98	-5.15	-8.3
10	-3.25	-5.72	-9.1
11	-3.55	-6.20	-10.0
12	-3.80	-6.75	-10.9
13	-4.08	-7.25	-11.8
14	-4.36	-7.75	-12.7
15	-4.62	-8.30	-13.6
16	-4.90	-8.80	-14.5
17	-5.18	-9.40	-15.3
18	-5.42	-9.80	-16.1
19	-5.70	-10.40	-16.9
20	-5.99	-10.98	-17.6
21	-6.26	-11.50	-18.4
22	-6.54	-12.00	-19.3
23	-6.82	-12.60	-20.2
24	-7.10	-13.20	-21.1
25	-7.40	-13.80	-22.0
26	-7.68	-14.30	-22.8
27	-7.96	-14.80	-23.6
28	-8.24	-15.40	-24.4
29	-8.52	-16.00	-25.2
30	-8.80	-16.50	-26.0
31	-9.10	-17.10	-26.7
32	-9.40	-17.60	-27.4
33	-9.66	-18.20	-28.0
34	-9.95	-18.80	-28.7
35	-10.24	-19.20	-29.4
36	-10.52	-19.80	-30.0

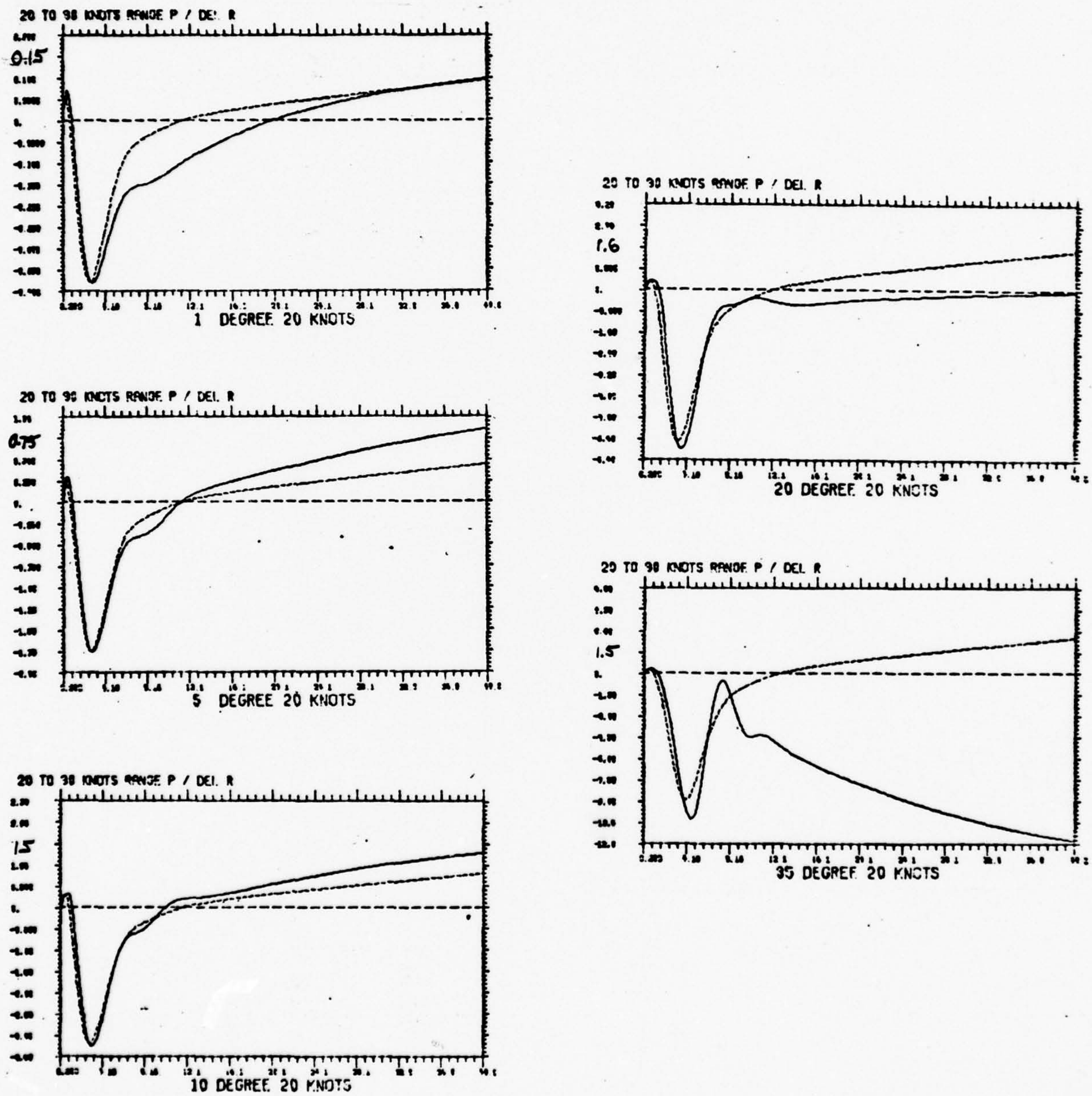


Fig. 31. P Versus δ_r, 20 Knots

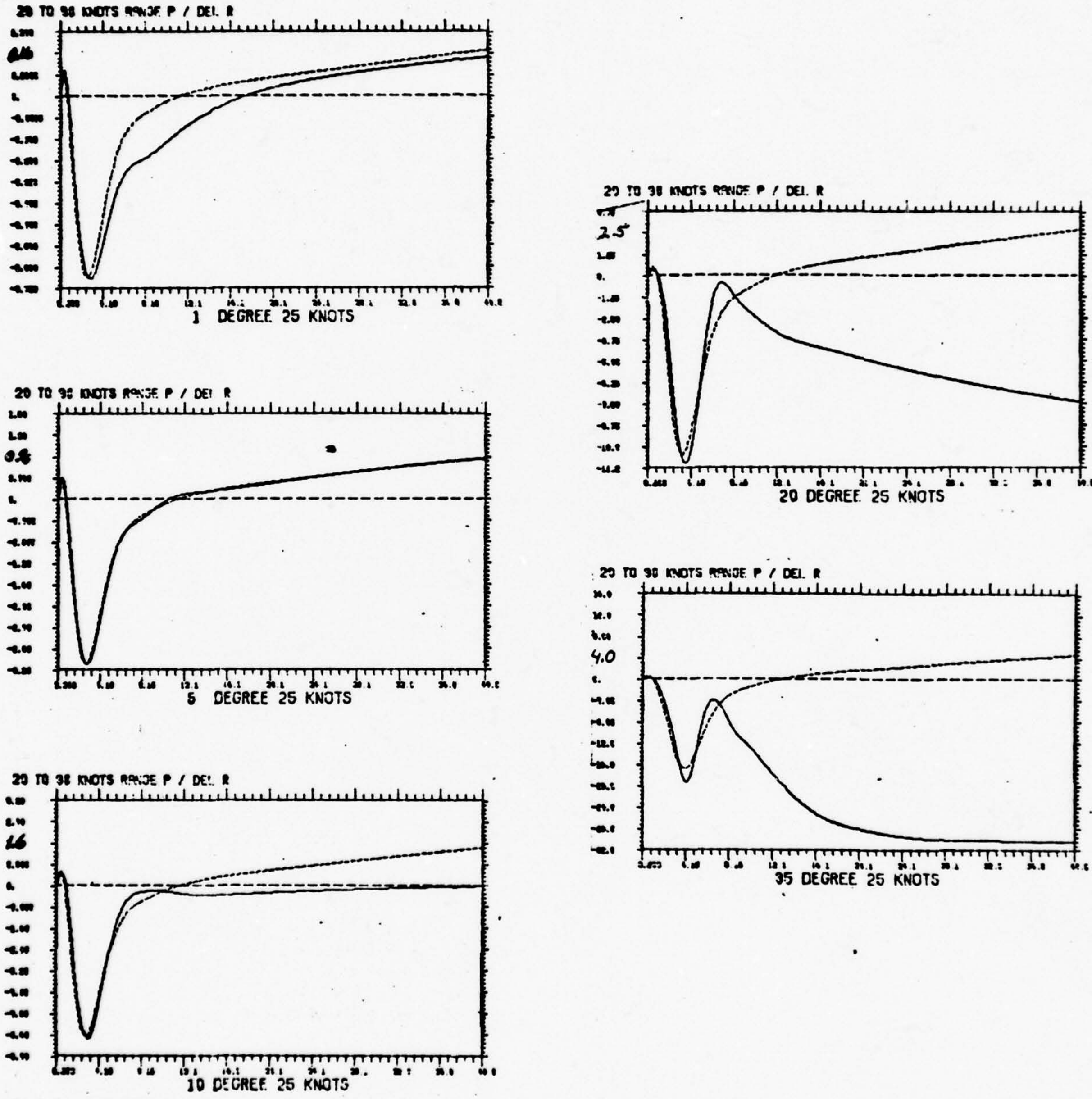


Fig. 32. P Versus δ_r, 25 Knots

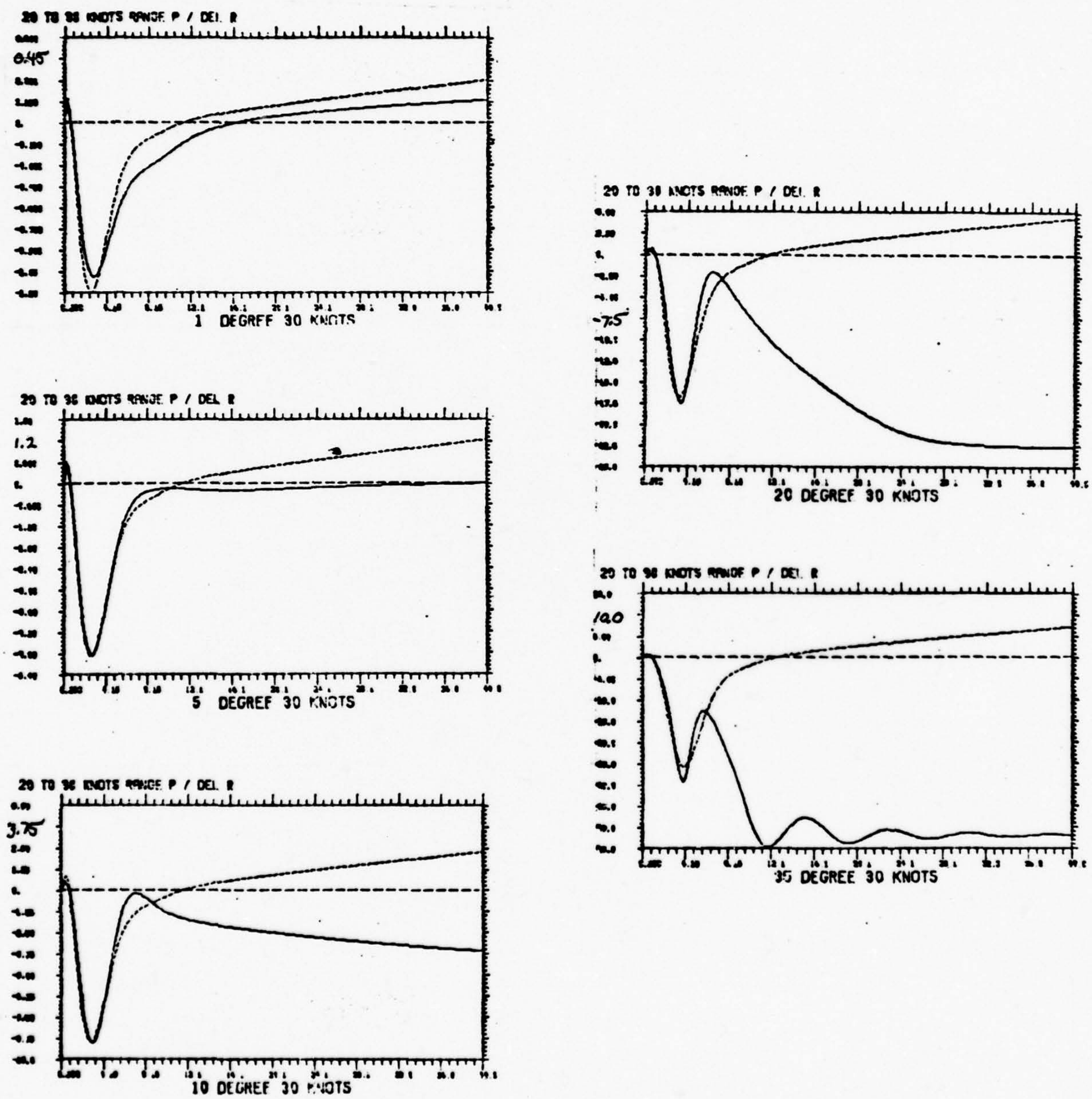
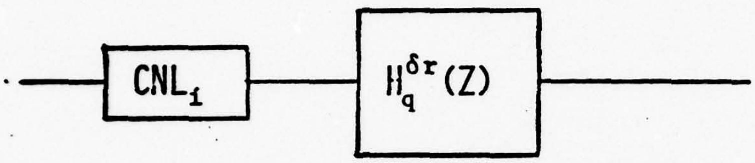


Fig. 33. P Versus δ_r, 30 Knots

RESULTS OF VALIDATION TESTS FOR: USF RPV

TRANSFER FUNCTION: $Q/\delta r$

MODEL:



U_o: 7.5 Knots

U_-: 5 Knots

U_+: 10 Knots

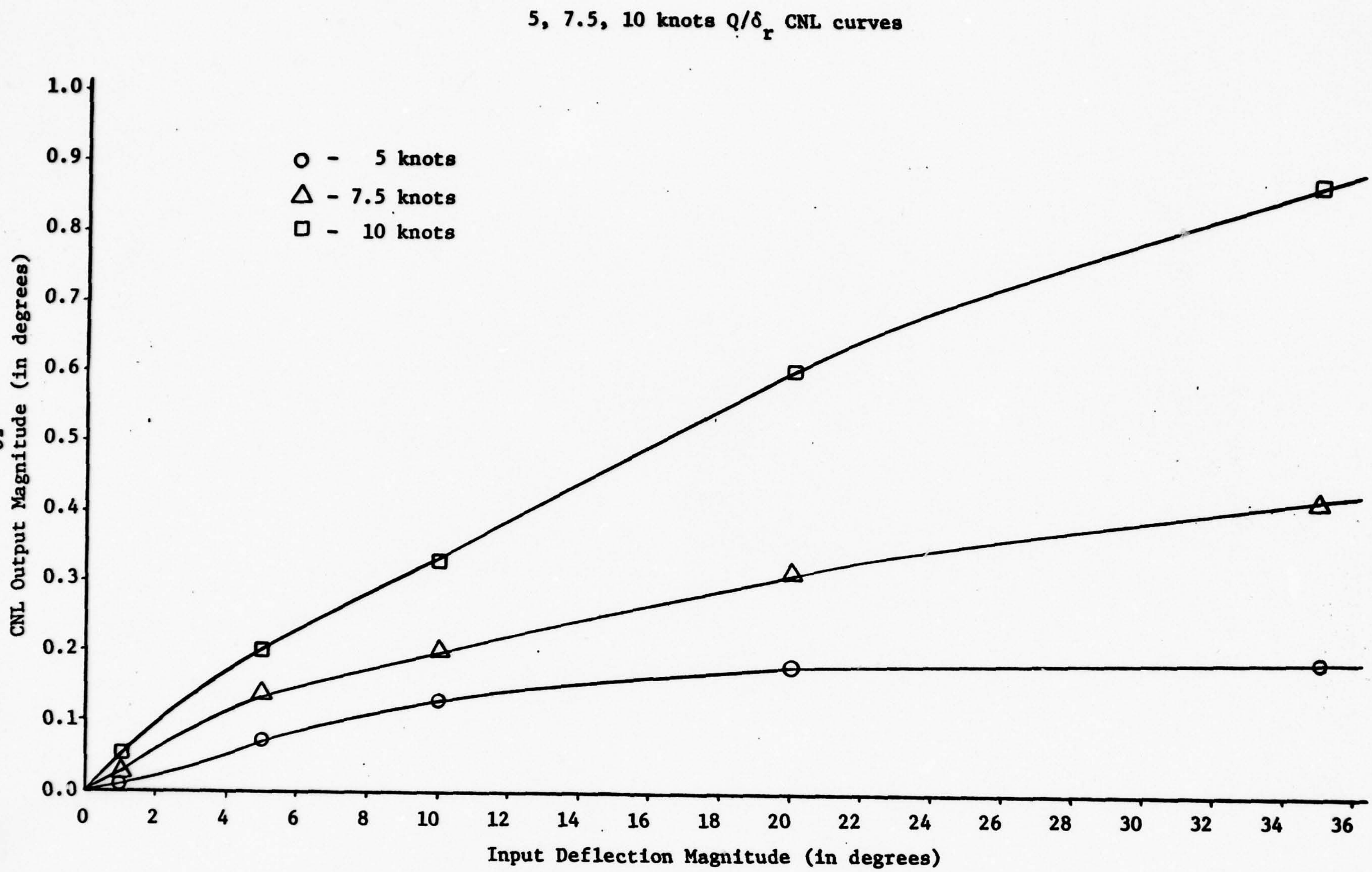
$H_q^{\delta r}(Z)$ DETERMINED USING U_o AND 5° δr STEP

$$H_q^{\delta r} = \frac{-9.526 \times 10^{-2}\, Z + 1.006 \times 10^{-2}}{Z^2 - 1.994Z + 9.945 \times 10^{-1}}$$

POLES IN THE s DOMAIN*

$-1.375 \times 10^{-2} \pm j\, 1.258 \times 10^{-1}$

*For conversion from Z-domain to S-domain, see references [11],[8].



5, 7.5, 10 knots Q/δr CNL curves
○ - 5 knots
△ - 7.5 knots
□ - 10 knots
CNL Output Magnitude (in degrees)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
Input Deflection Magnitude (in degrees)

Fig. 33

Table 13

Custom nonlinearity (CNL): Q versus δ_r

5-10 knot range

δ_r	Q steady state		
Degree	5 knots	7.5 knots	10 knots
0	0.000	0.000	0.000
1	0.008	0.028	0.054
2	0.020	.057	0.093
3	0.038	.083	0.133
4	0.057	.111	0.170
5	0.076	0.139	0.203
6	0.089	.152	0.230
7	0.100	.168	0.257
8	0.111	.180	0.282
9	0.120	.90	0.309
10	0.129	0.200	0.328
11	0.136	.210	0.360
12	0.142	.220	0.385
13	0.148	.230	0.416
14	0.152	.241	0.440
15	0.158	.252	0.468
16	0.162	.266	0.492
17	0.167	.279	0.522
18	0.170	.290	0.549
19	0.175	.301	0.578
20	0.177	0.314	0.600
21	0.180	.322	0.623
22	0.180	.331	0.645
23	0.180	.340	0.665
24	0.180	.349	0.682
25	0.180	.357	0.701
26	0.180	.362	0.720
27	0.181	.371	0.739
28	0.183	.379	0.757
29	0.184	.385	0.773
30	0.184	.390	0.780
31	0.184	.399	0.807
32	0.184	.402	0.823
33	0.184	.410	0.840
34	0.184	.415	0.857
35	0.184	0.424	0.870
36	0.185	.425	0.888

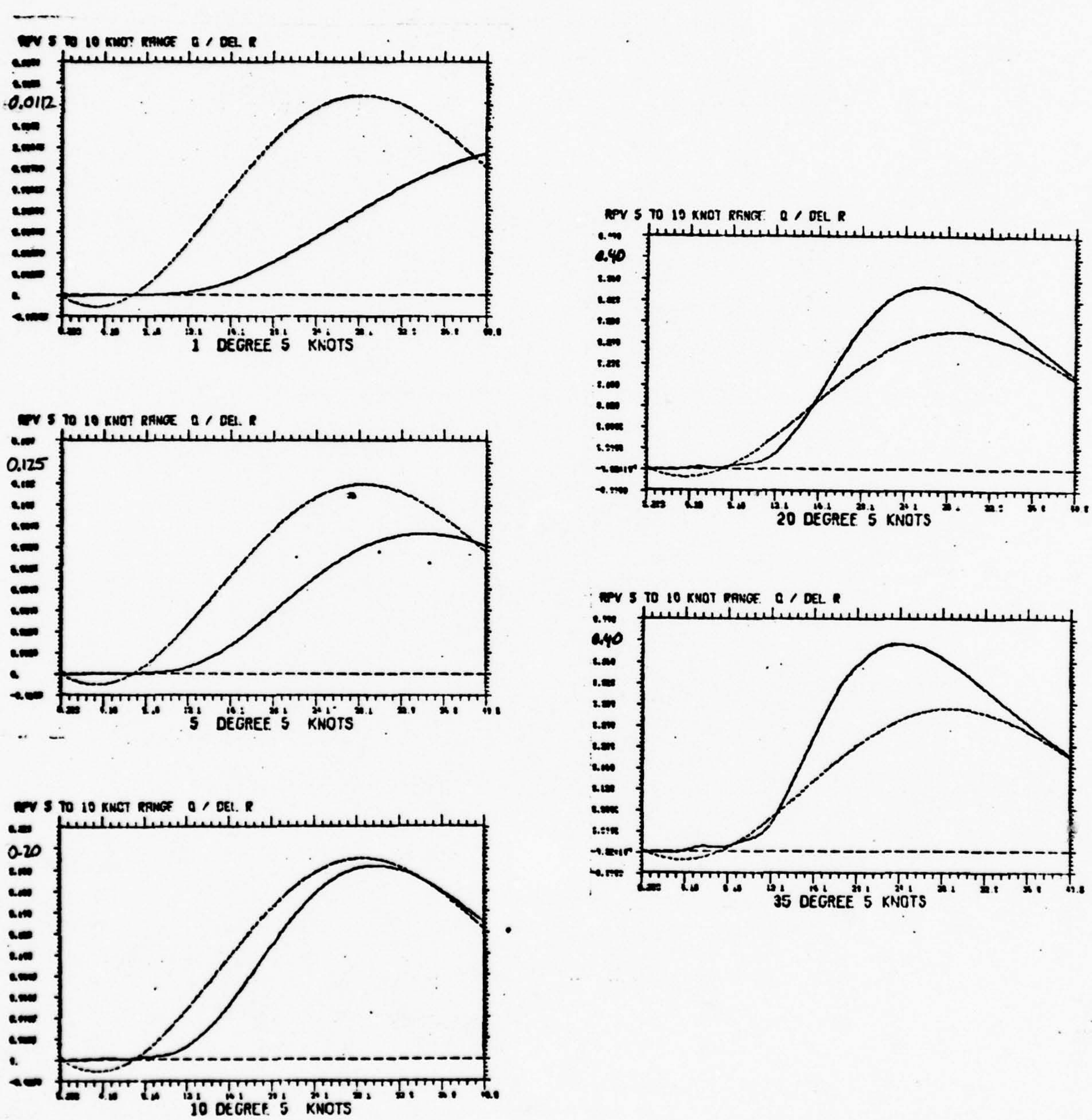


Fig. 35. Q Versus δ_r, 5 Knots

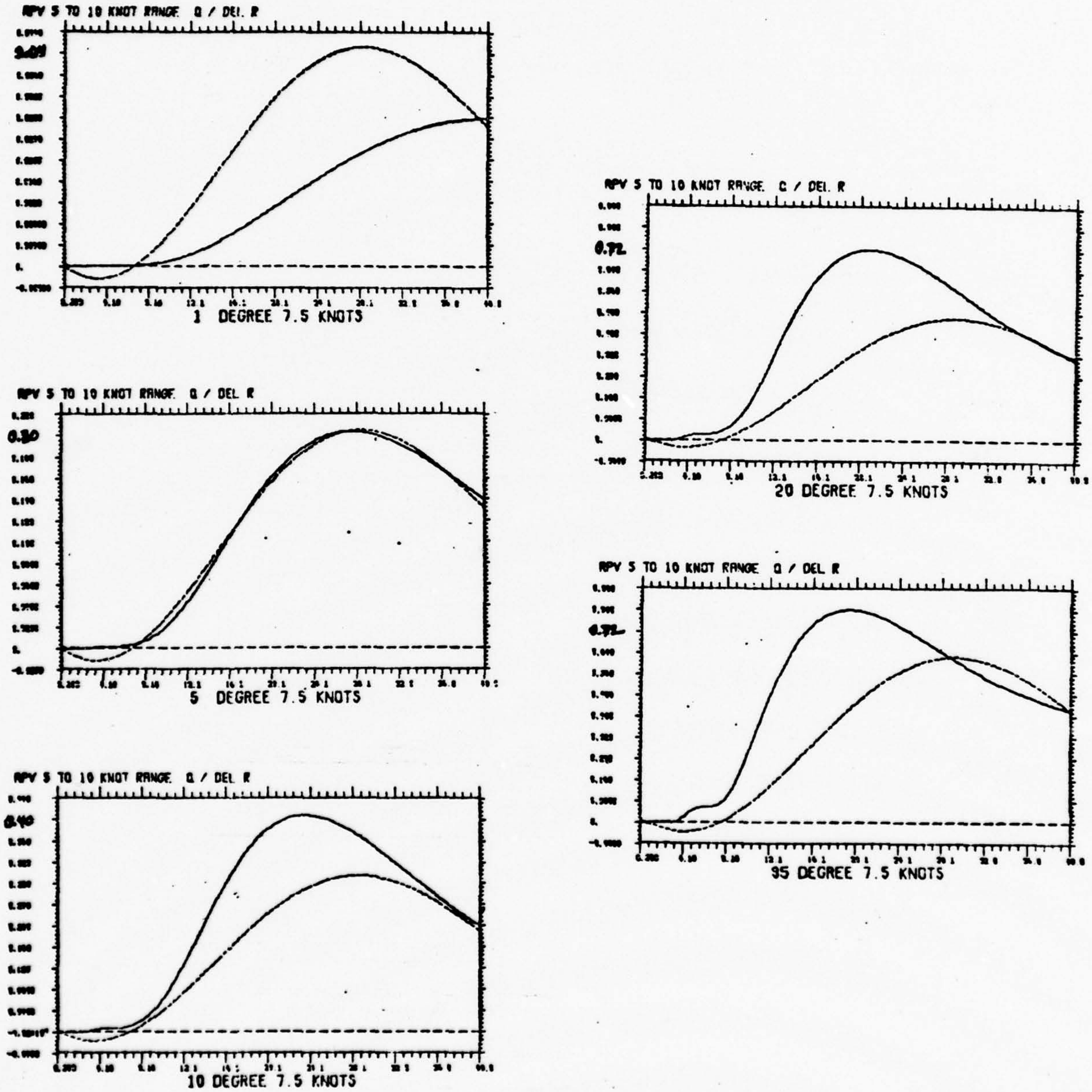


Fig. 36. Q Versus δ_r, 7.5 Knots

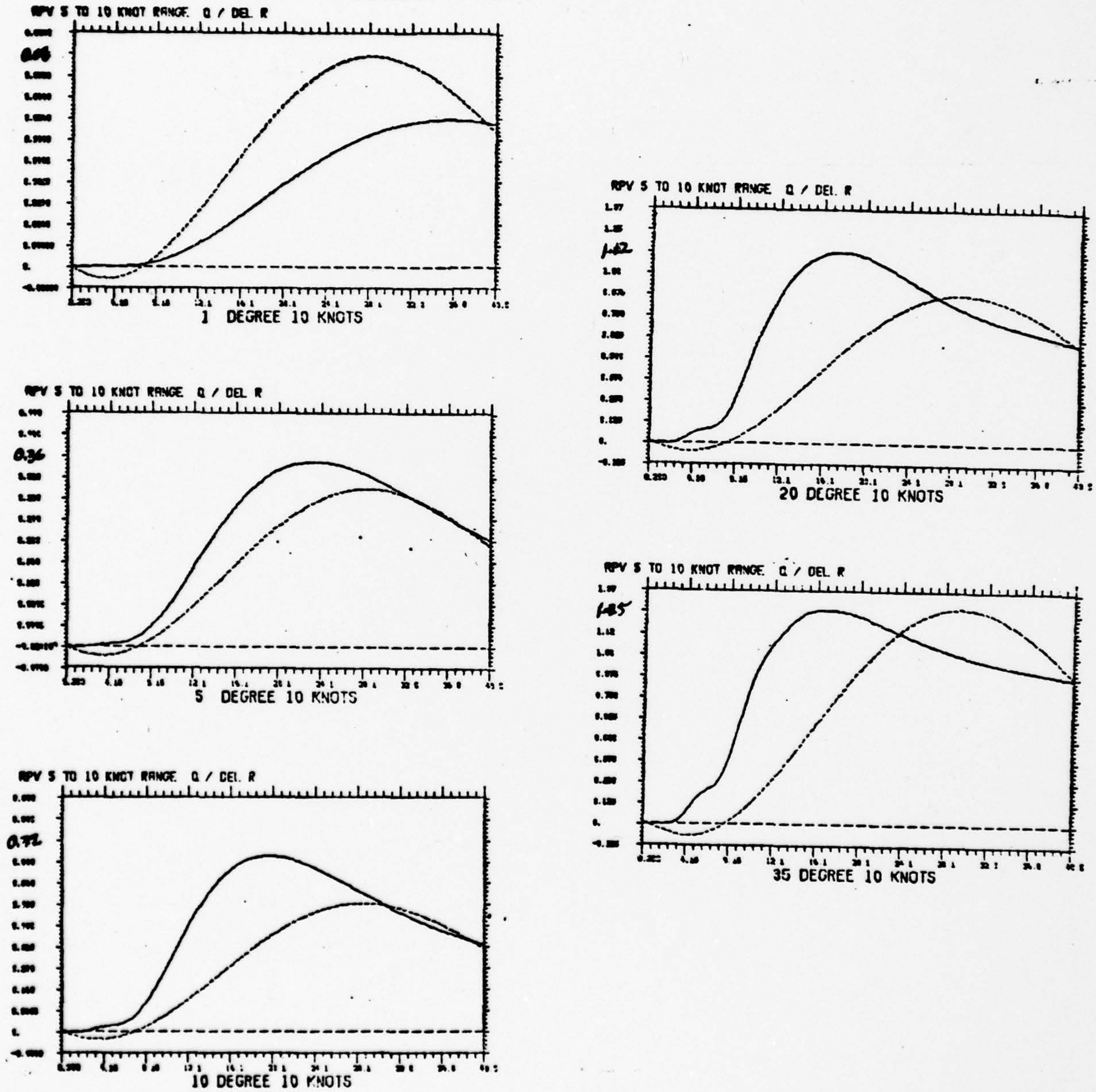
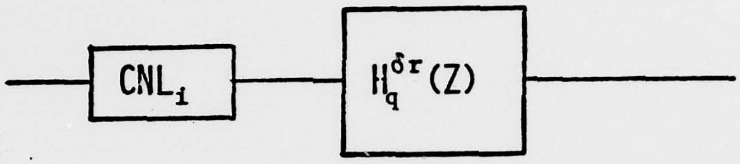


Fig. 37. Q Versus δ_r, 10 Knots

RESULTS OF VALIDATION TESTS FOR: USF RPV

TRANSFER FUNCTION: $Q/\delta r$

MODEL:



U_o: 15 Knots

U_-: 10 Knots

U_+: 20 Knots

$H_q^{\delta r}(Z)$ DETERMINED USING U_o AND 5° δr STEP

$$H_q^{\delta r} = \frac{-1.281 \times 10^{-2} Z + 1.453 \times 10^{-2}}{Z^2 - 1.974Z + 9.754 \times 10^{-1}}$$

POLES IN THE S DOMAIN*

$$-6.219 \times 10^{-2} \pm j\ 1.758 \times 10^{-1}$$

*For conversion from Z-domain to S-domain, see references [11],[8].

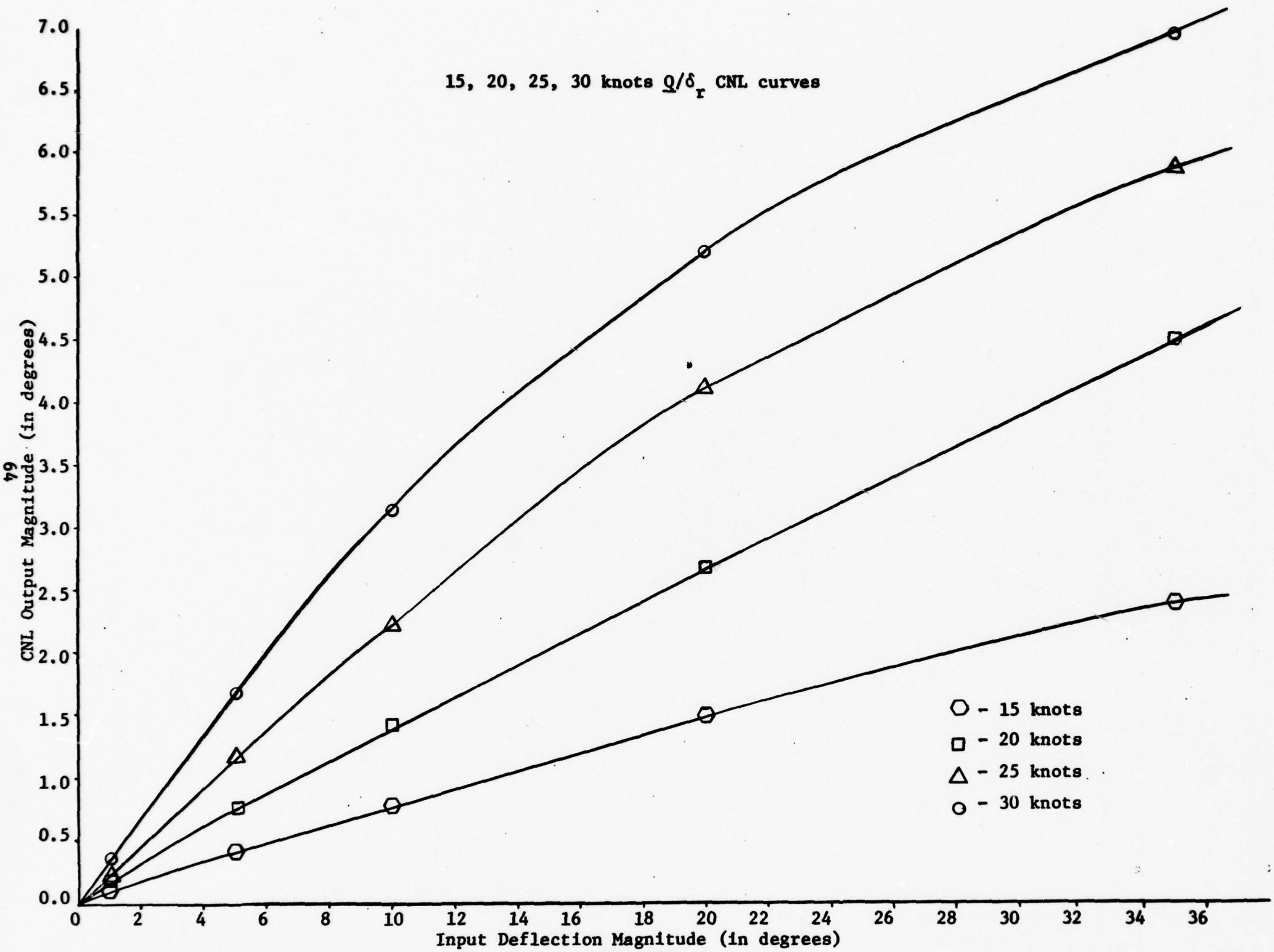

15, 20, 25, 30 knots $\underline{Q}/\delta_r$ CNL curves
CNL Output Magnitude (in degrees)
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
Input Deflection Magnitude (in degrees)
⬡ - 15 knots
□ - 20 knots
△ - 25 knots
○ - 30 knots

Fig. 38

Table 14

Custom nonlinearity (CNL): Q versus δ_r

10-20 knot range

δ_r	Q steady state		
Degree	10 knots	15 knots	20 knots
0	0.000	0.00	0.00
1	0.054	0.11	0.18
2	0.093	0.18	0.34
3	0.133	0.26	0.49
4	0.170	0.34	0.64
5	0.203	0.41	0.76
6	0.230	0.49	0.90
7	0.257	0.57	1.05
8	0.282	0.64	1.18
9	0.309	0.71	1.31
10	0.328	0.78	1.43
11	0.360	0.85	1.56
12	0.385	0.92	1.68
13	0.416	0.99	1.81
14	0.440	1.06	1.93
15	0.468	1.14	2.06
16	0.492	1.21	2.19
17	0.522	1.28	2.31
18	0.549	1.36	2.43
19	0.578	1.43	2.55
20	0.600	1.50	2.68
21	0.623	1.56	2.80
22	0.645	1.64	2.92
23	0.665	1.70	3.04
24	0.682	1.77	3.16
25	0.701	1.84	3.28
26	0.720	1.90	3.41
27	0.739	1.96	3.53
28	0.757	2.03	3.65
29	0.773	2.08	3.76
30	0.780	2.14	3.90
31	0.807	2.20	4.02
32	0.823	2.25	4.14
33	0.840	2.30	4.25
34	0.857	2.35	4.37
35	0.870	2.40	4.49
36	0.888	2.45	4.66

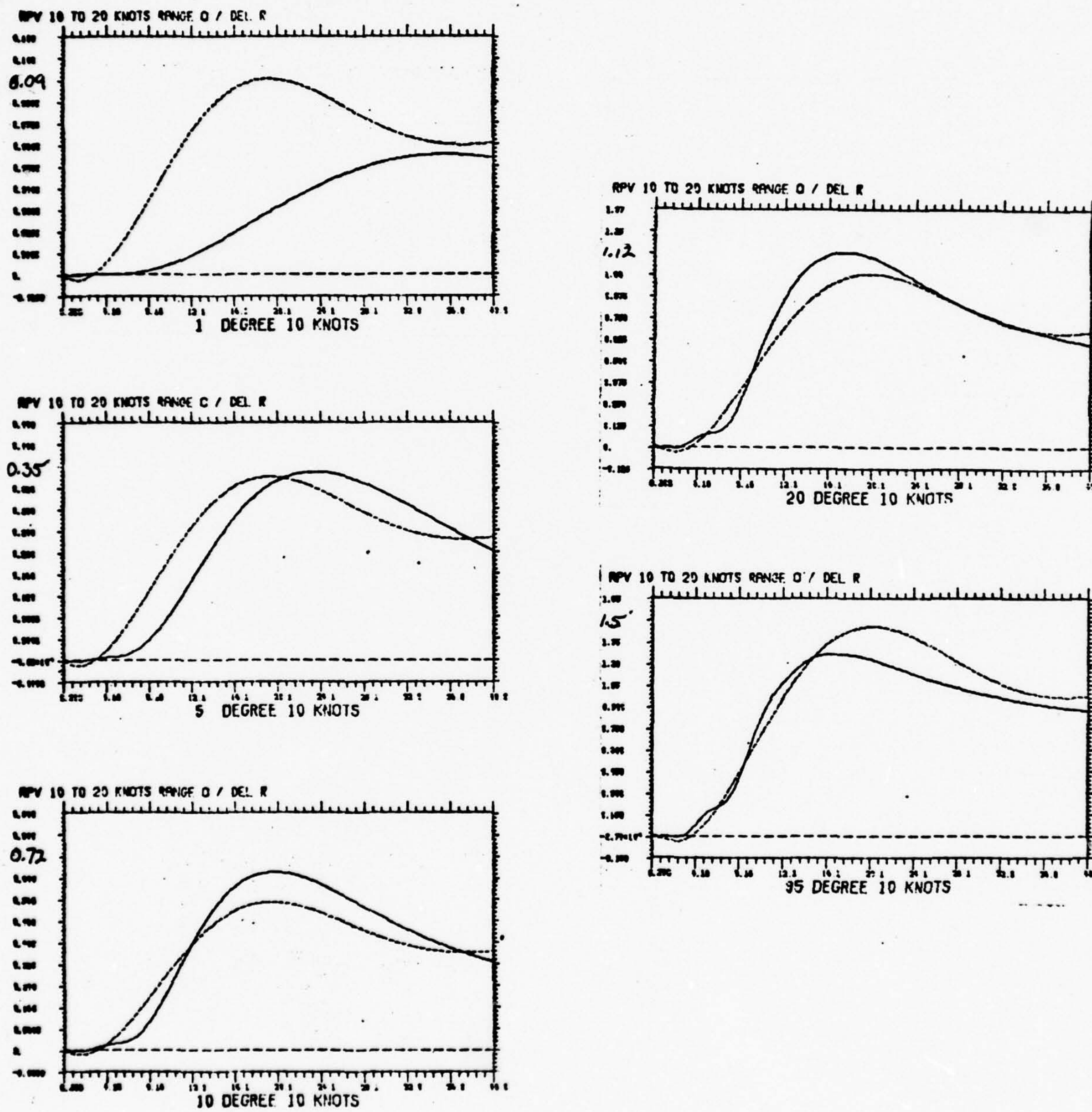


Fig. 39. Q Versus δ_r, 10 Knots

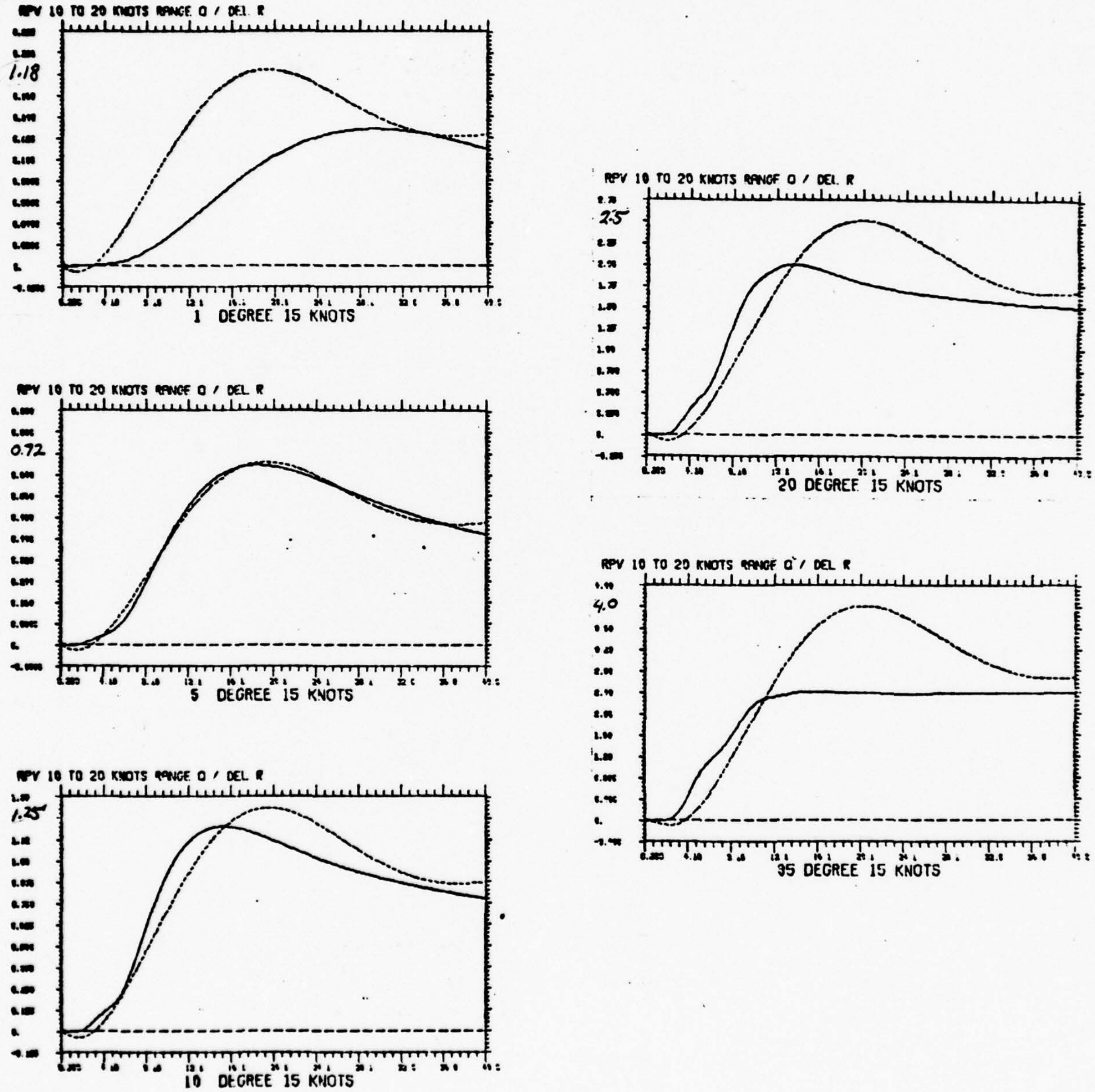


Fig. 40. Q Versus δ_r, 15 Knots

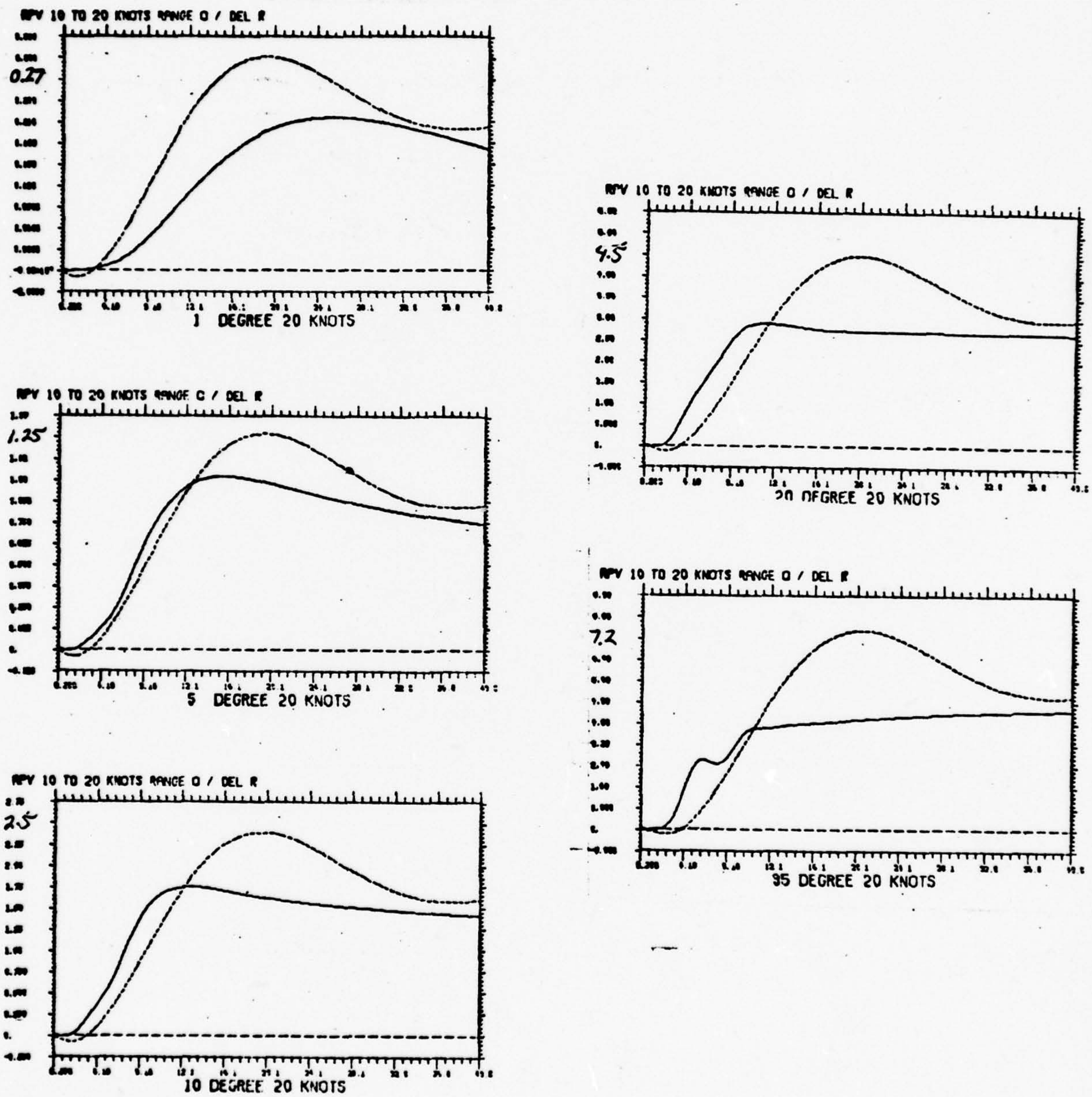
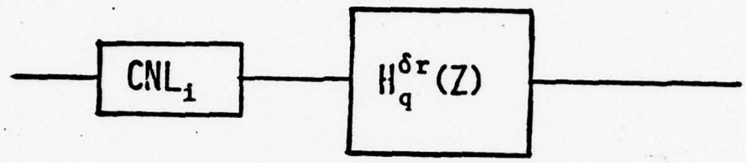


Fig. 41. Q Versus δ_r, 20 Knots

RESULTS OF VALIDATION TESTS FOR: USF RPV

TRANSFER FUNCTION: Q/δr

MODEL:



U_o: 25 Knots

U_-: 20 Knots

U_+: 30 Knots

$H_q^{\delta r}(Z)$ DETERMINED USING U_o AND 5° δr STEP

$$H_q^{\delta r} = \frac{-5.831 \times 10^{-2} Z + 8.861 \times 10^{-2}}{Z^2 - 1.939Z + 9.423 \times 10^{-1}}$$

POLES IN THE S DOMAIN*

$$-1.486 \times 10^{-1} \pm j\, 2.283 \times 10^{-1}$$

*For conversion from Z-domain to S-domain, see references [11],[8].

Table 15

Custome nonlinearity (CNL): Q versus δ_r

20-30 knot range

δ_r	Q steady state		
Degree	20 knots	25 knots	30 knots
0	0.00	0.00	0.00
1	0.18	0.26	0.41
2	0.34	0.49	0.69
3	0.49	0.72	1.02
4	0.64	0.95	1.35
5	0.76	1.18	1.68
6	0.90	1.39	2.00
7	1.05	1.60	2.29
8	1.18	1.80	2.58
9	1.31	2.00	2.85
10	1.43	2.22	3.14
11	1.56	2.42	3.38
12	1.68	2.61	3.59
13	1.81	2.80	3.80
14	1.93	2.99	4.02
15	2.06	3.18	4.22
16	2.19	3.37	4.43
17	2.31	3.56	4.64
18	2.43	3.74	4.83
19	2.55	3.91	5.02
20	2.68	4.08	5.18
21	2.80	4.25	5.35
22	2.92	4.40	5.49
23	3.04	4.52	5.62
24	3.16	4.65	5.75
25	3.28	4.77	5.88
26	3.41	4.89	5.98
27	3.53	5.00	6.10
28	3.65	5.12	6.21
29	3.76	5.24	6.28
30	3.90	5.35	6.44
31	4.02	5.45	6.54
32	4.14	5.55	6.65
33	4.25	5.66	6.75
34	4.37	5.76	6.85
35	4.49	5.86	6.92
36	4.66	5.96	7.00

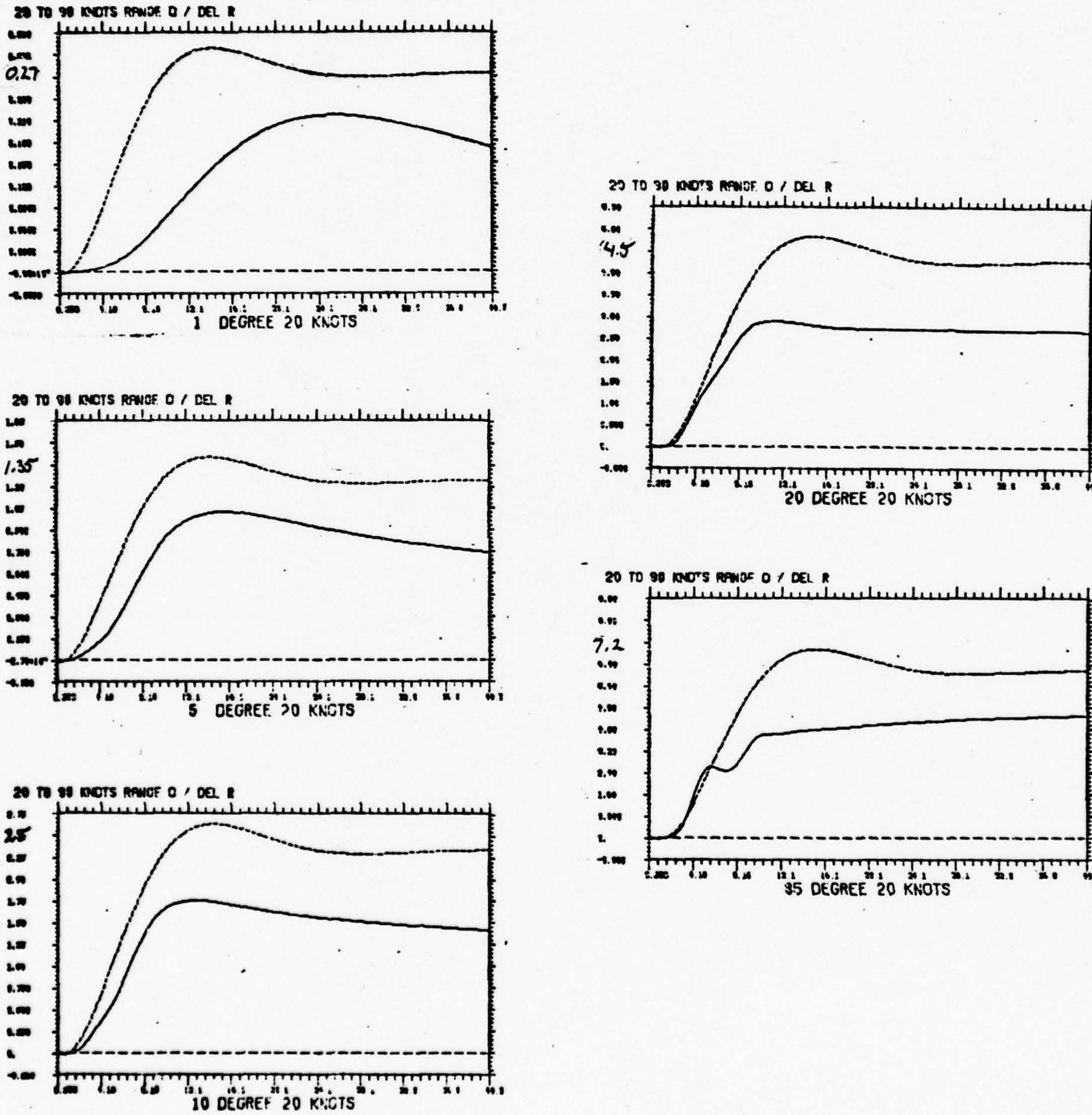


Fig. 42. Q Versus δ_r, 20 Knots

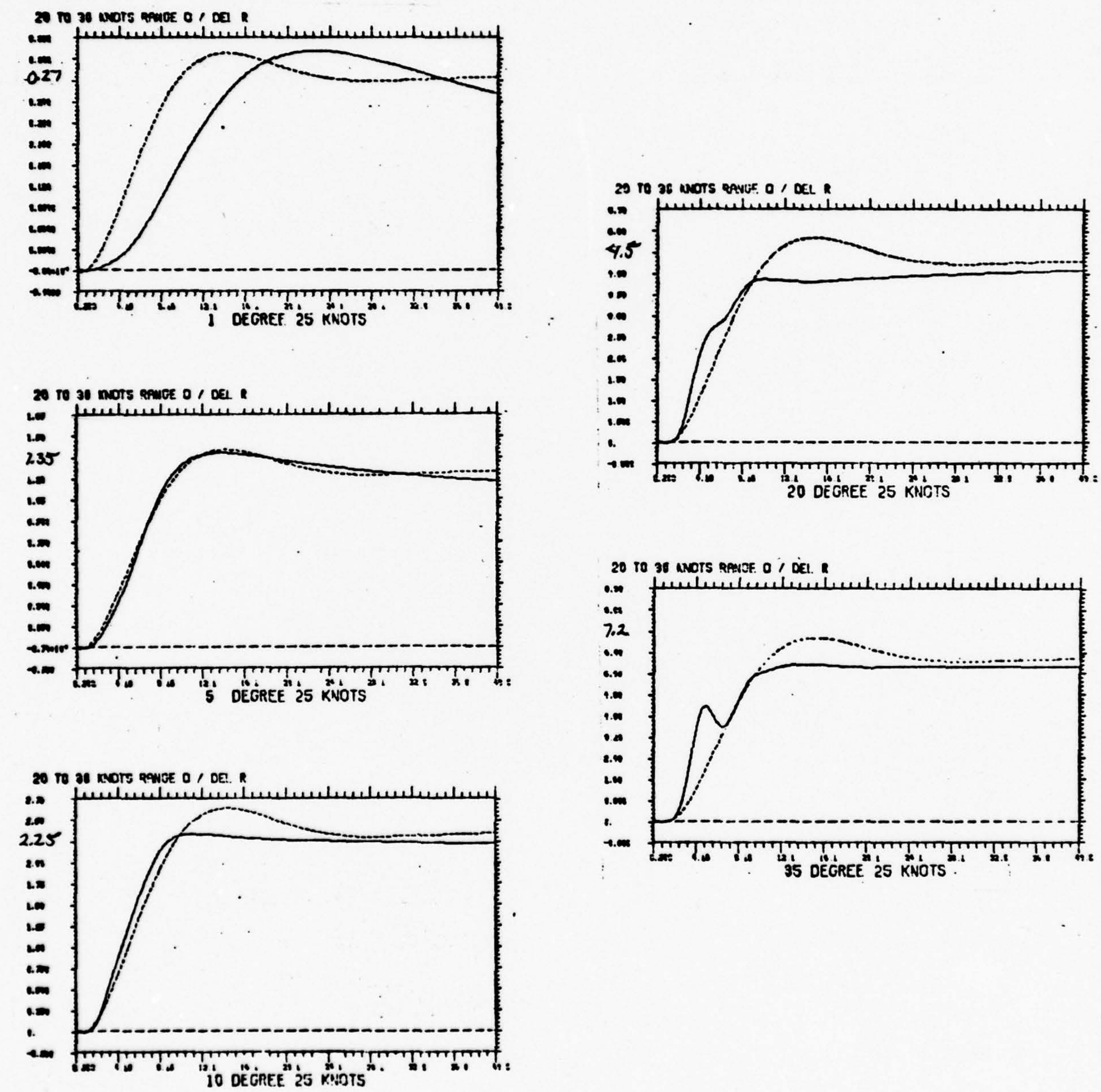


Fig. 43. Q Versus δ_r, 25 Knots

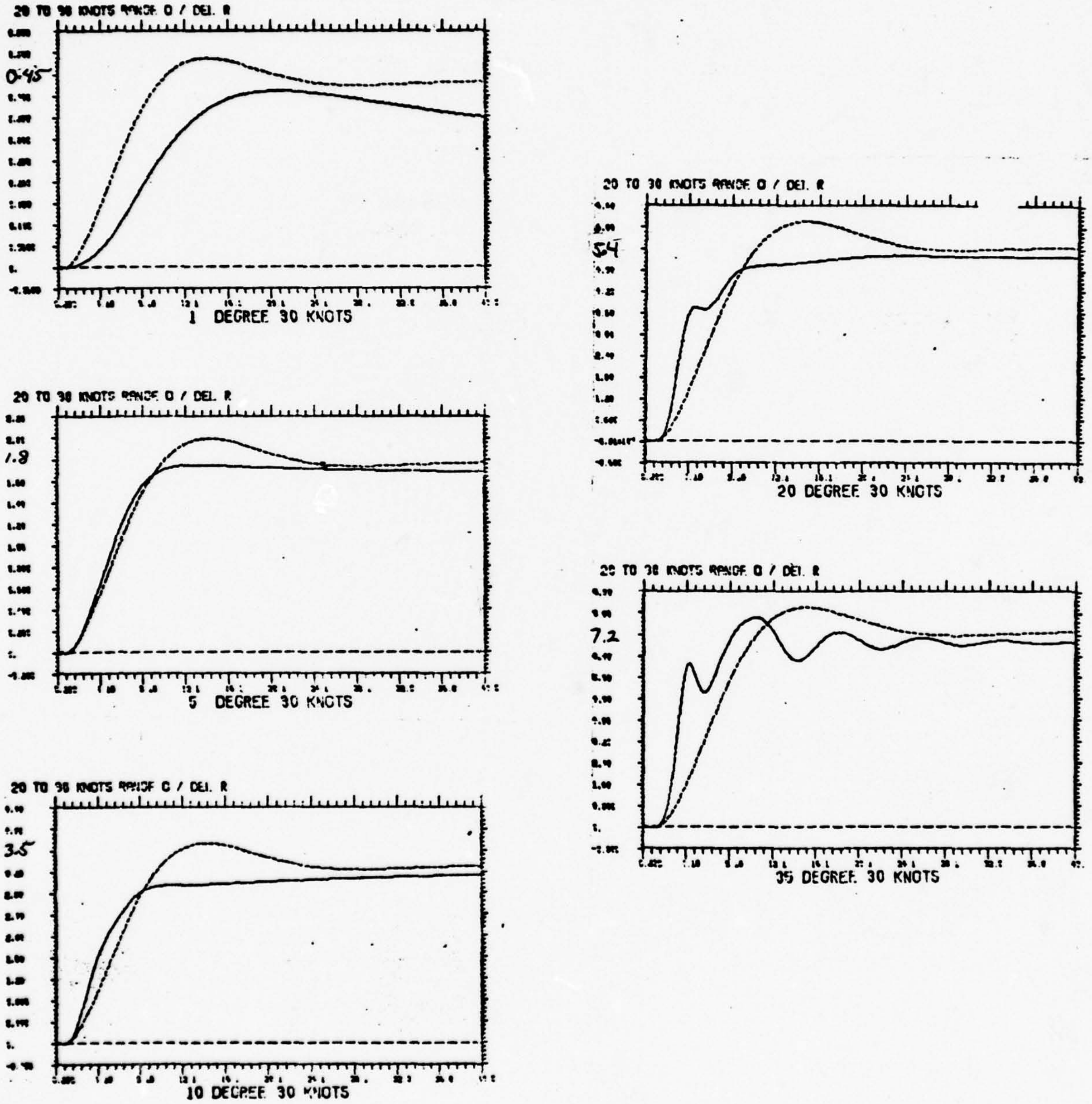
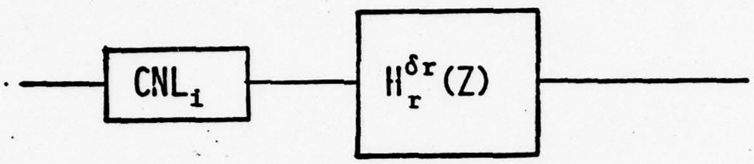


Fig. 44. Q Versus δ_r, 30 Knots

Results of Validation Tests For: USF RPV

Transfer Function: $R/\delta r$

Model:



U_o: 7.5 Knots

U_-: 5 Knots

U_+: 10 Knots

$H_r^{\delta r}(Z)$ Determined Using U_o and 5° δr Step

$$H_r^{\delta r} = \frac{2.575 \times 10^{-2} Z - 2.570 \times 10^{-2}}{Z^2 - 1.974Z + 9.743 \times 10^{-1}}$$

Poles in the s Domain*

-1.539×10^{-2}

-1.146×10^{-1}

*For conversion from Z-domain to S-domain, see references [11],[8].

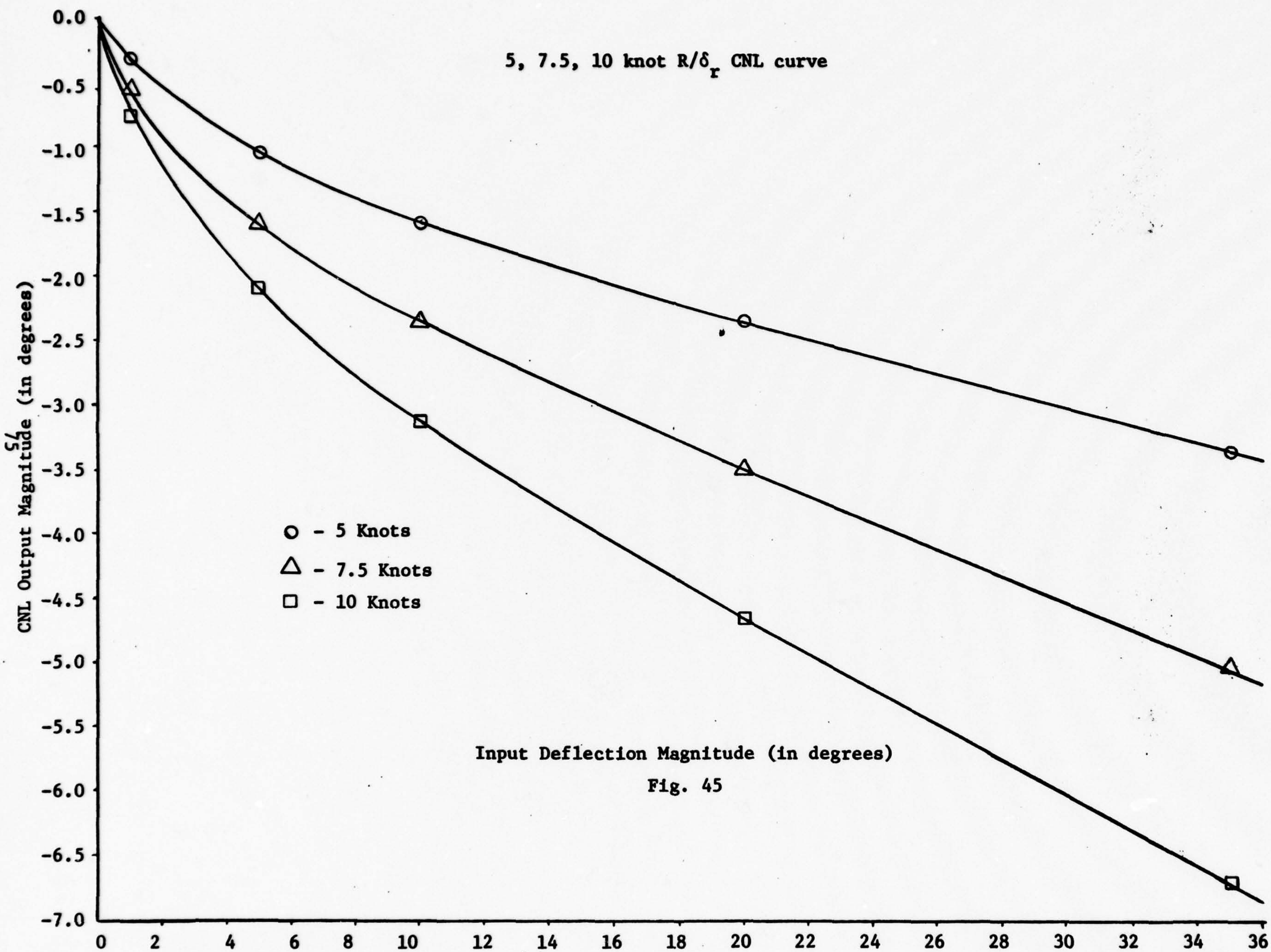

5, 7.5, 10 knot R/δ_r CNL curve
CNL Output Magnitude (in degrees)
Input Deflection Magnitude (in degrees)
○ - 5 Knots
△ - 7.5 Knots
□ - 10 Knots
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
-4.5
-5.0
-5.5
-6.0
-6.5
-7.0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36

Fig. 45

Table 16

Custom nonlinearity (CNL): R versus δ_r

5-10 knot range

δ_r	R steady state		
Degree	5 knots	7.5 knots	10 knots
0	0.0	0.00	0.00
1	-0.32	-0.53	-0.79
2	- .55	- .90	-1.20
3	- .72	-1.15	-1.55
4	- .88	-1.38	-1.85
5	-1.06	-1.59	-2.10
6	-1.16	-1.77	-2.35
7	-1.30	-1.94	-2.56
8	-1.40	-2.08	-2.77
9	-1.50	-2.22	-2.95
10	-1.60	-2.35	-3.13
11	-1.67	-2.47	-3.30
12	-1.77	-2.60	-3.47
13	-1.85	-2.71	-3.63
14	-1.93	-2.83	-3.78
15	-2.00	-2.95	-3.95
16	-2.07	-3.05	-4.08
17	-2.15	-3.17	-4.23
18	-2.23	-3.27	-4.38
19	-2.30	-3.40	-4.52
20	-2.36	-3.52	-4.68
21	-2.44	-3.60	-4.80
22	-2.50	-3.70	-4.95
23	-2.57	-3.80	-5.08
24	-2.63	-3.92	-5.23
25	-2.70	-4.02	-5.35
26	-2.78	-4.13	-5.55
27	-2.84	-4.23	-5.63
28	-2.90	-4.32	-5.77
29	-2.96	-4.44	-5.90
30	-3.04	-4.55	-6.04
31	-3.10	-4.65	-6.16
32	-3.16	-4.75	-6.30
33	-3.23	-4.85	-6.44
34	-3.33	-5.00	-6.58
35	-3.37	-5.06	-6.70
36	-3.43	-5.	-6.85

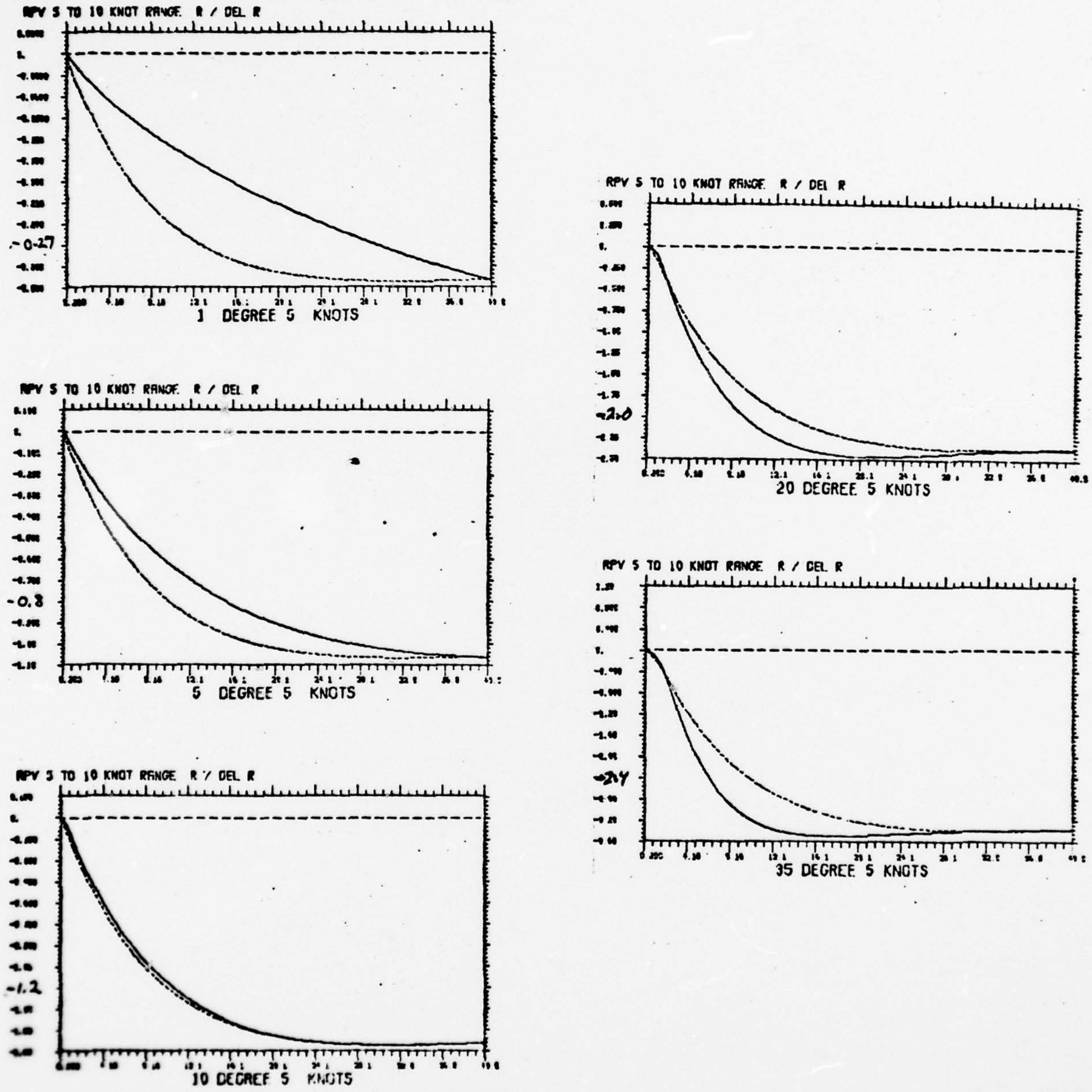


Fig. 46. R Versus δ_r, 5 Knots

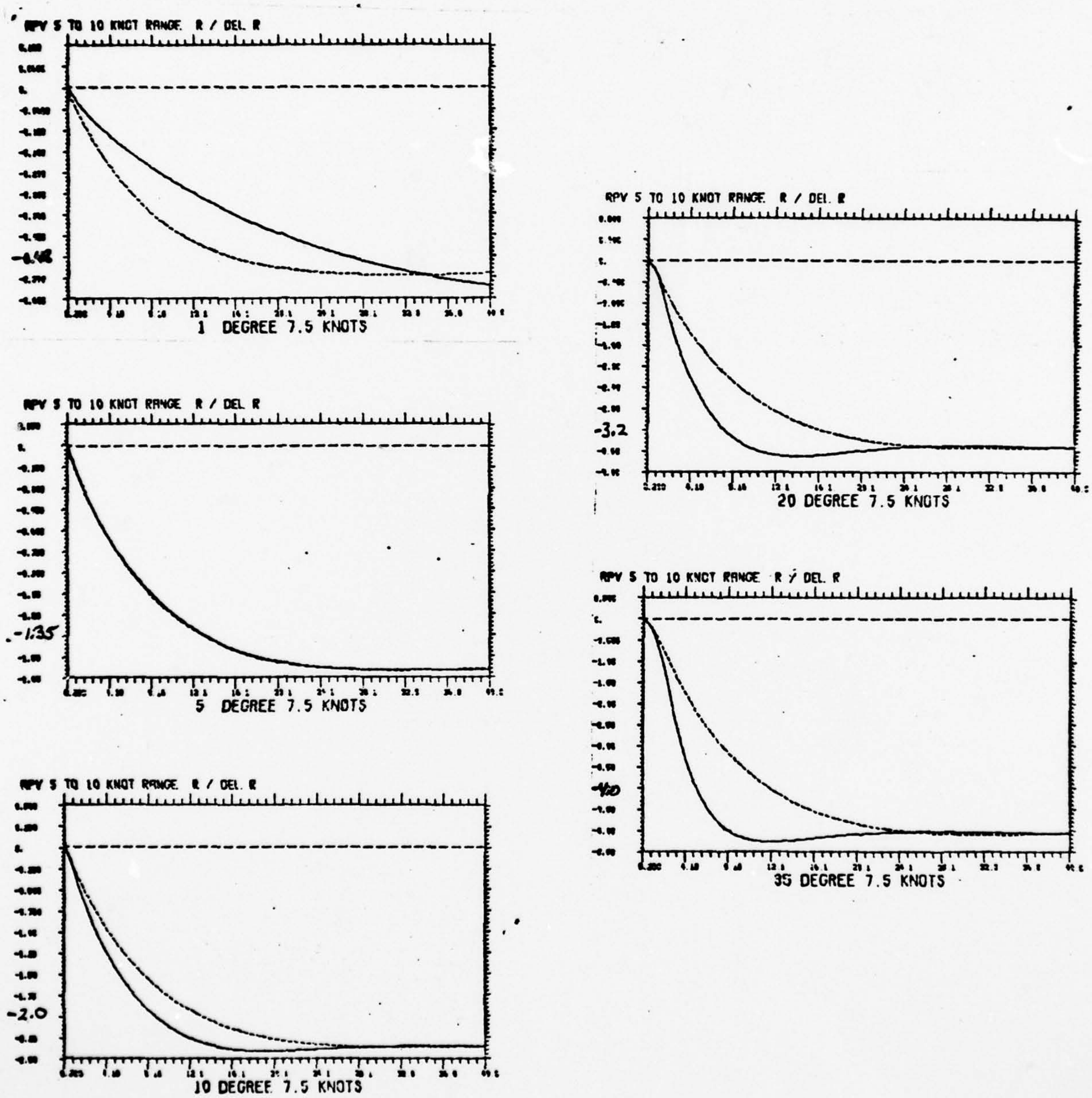


Fig. 47. R Versus δ_r, 7.5 Knots

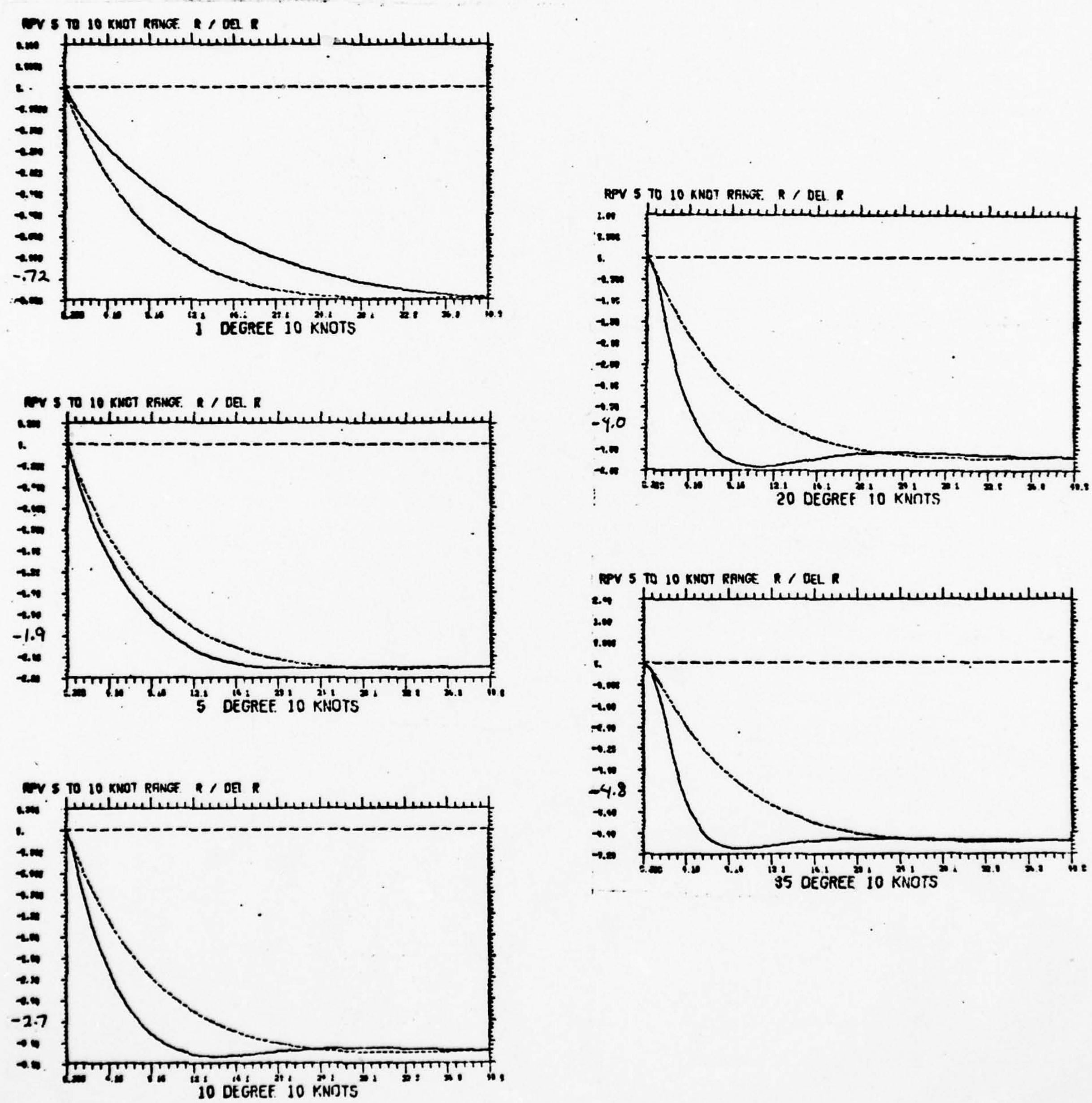
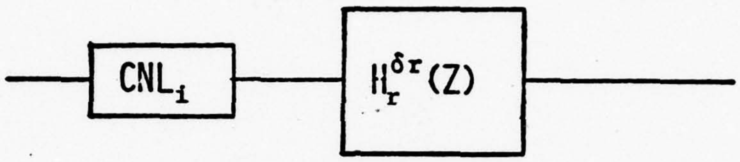


Fig. 48. R Versus δ_r, 10 Knots

Results of Validation Tests For: USF RPV

Transfer Function: $R/\delta r$

Model:



U_o: 15 Knots

U_-: 10 Knots

U_+: 20 Knots

$H_r^{\delta r}(Z)$ Determined Using U_o and 5° δr Step

$$H_r^{\delta r} = \frac{4.798 \times 10^{-2} Z - 4.491 \times 10^{-2}}{Z^2 - 1.903Z + 9.061 \times 10^{-1}}$$

Poles in the s Domain*

$-2.466 \times 10^{-1} \pm j\, 1.415 \times 10^{-1}$

*For conversion from Z-domain to S-domain, see references [11],[8].

15, 20, 25, and 30 Knot R/δr CNL curves

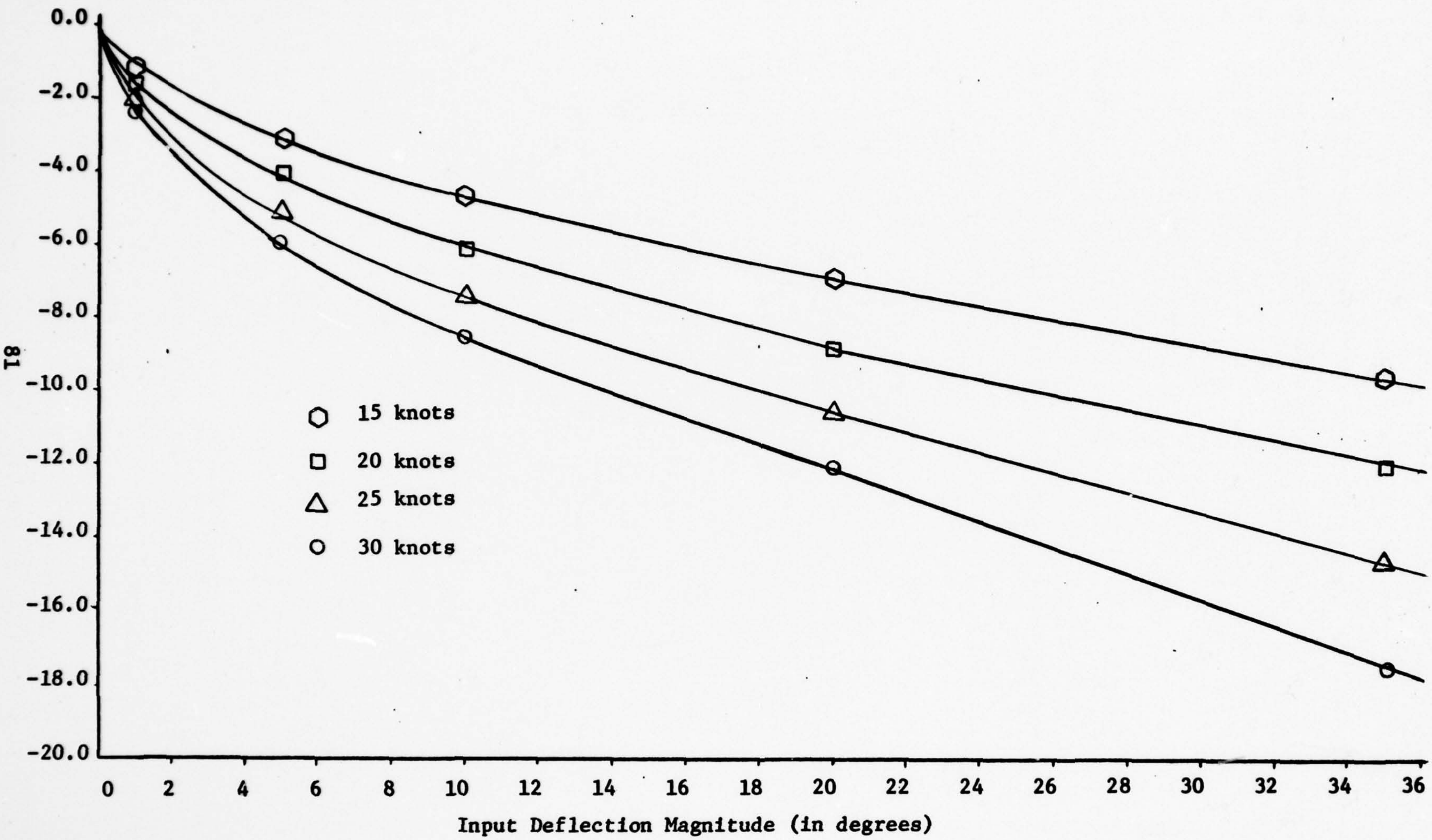


Fig. 49

Table 17

Custom nonlinearity (CNL): R versus δ_r

10-20 knot range

δ_r	R steady state		
Degree	10 knots	15 knots	20 knots
0	0.00	0.00	0.00
1	-0.79	-1.20	-1.61
2	-1.20	-1.75	-2.40
3	-1.55	-2.25	-3.00
4	-1.85	-2.75	-3.60
5	-2.10	-3.10	-4.08
6	-2.35	-3.52	-4.55
7	-2.56	-3.90	-5.00
8	-2.77	-4.20	-5.40
9	-2.95	-4.42	-5.80
10	-3.13	-4.70	-6.14
11	-3.30	-5.00	-6.40
12	-3.47	-5.25	-6.70
13	-3.63	-5.45	-7.00
14	-3.78	-5.70	-7.20
15	-3.95	-5.95	-7.50
16	-4.08	-6.15	-7.80
17	-4.23	-6.35	-8.05
18	-4.38	-6.50	-8.35
19	-4.52	-6.75	-8.60
20	-4.68	-7.00	-8.90
21	-4.80	-7.17	-9.15
22	-4.95	-7.30	-9.30
23	-5.08	-7.50	-9.55
24	-5.23	-7.70	-9.75
25	-5.35	-7.90	-9.95
26	-5.55	-8.10	-10.15
27	-5.63	-8.21	-10.35
28	-5.77	-8.40	-10.55
29	-5.90	-8.60	-10.75
30	-6.04	-8.80	-11.00
31	-6.16	-9.00	-11.20
32	-6.30	-9.15	-11.40
33	-6.44	-9.30	-11.60
34	-6.58	-9.50	-11.80
35	-6.70	-9.70	-12.00
36	-6.85	-9.80	-12.20

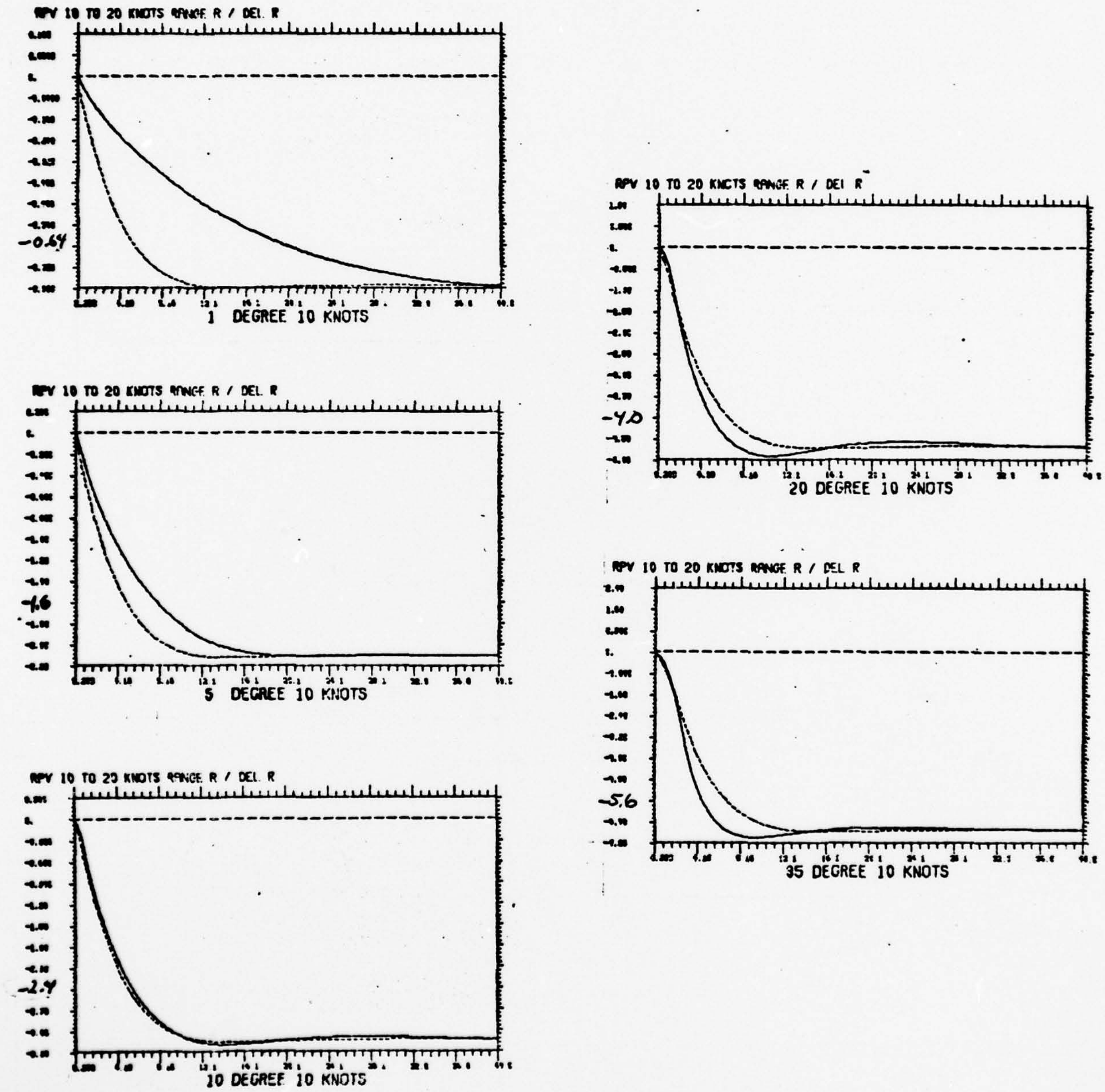


Fig. 50. R. Versus δ_r, 10 Knots

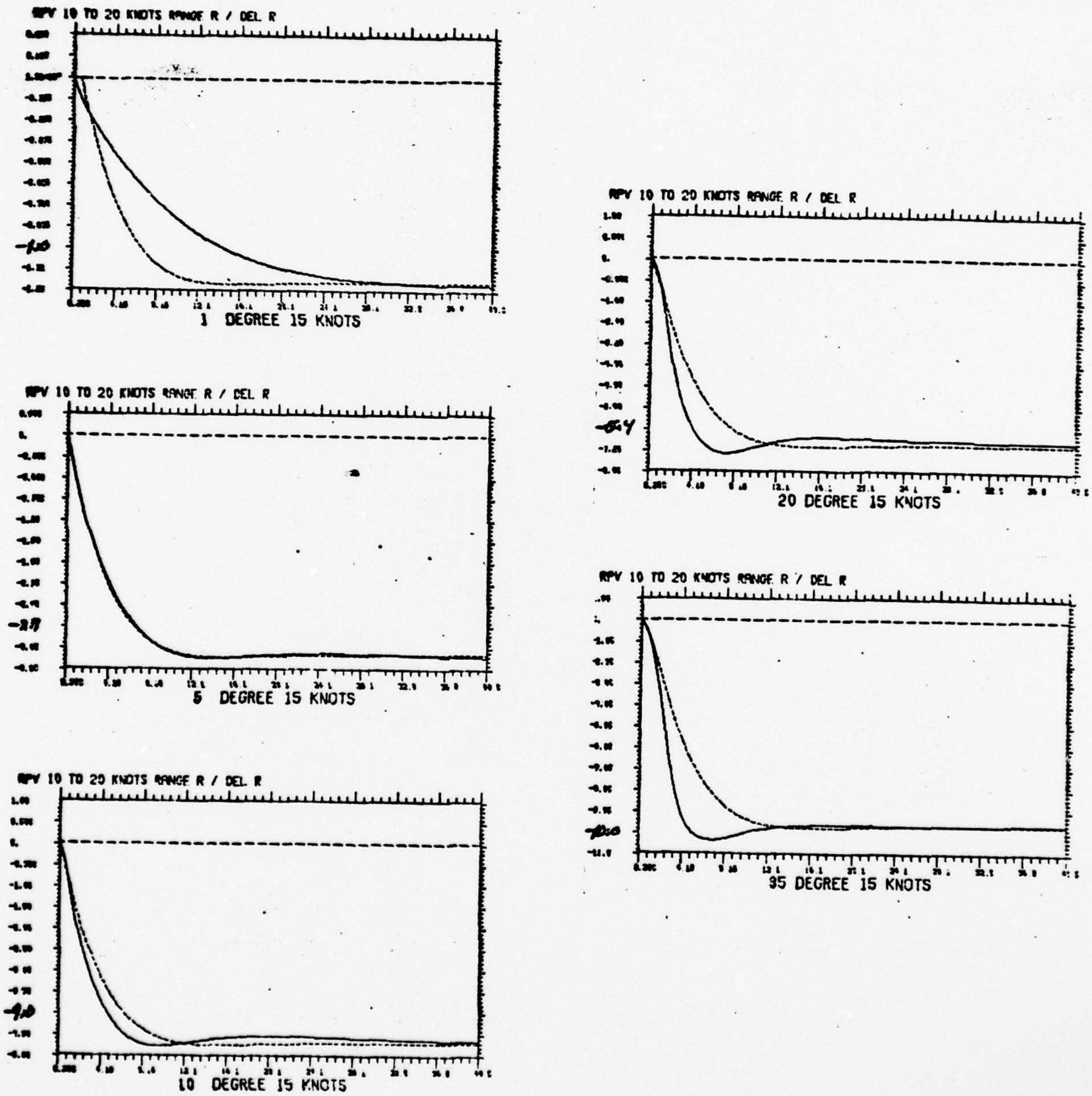


Fig. 51. R Versus δ_r, 15 Knots

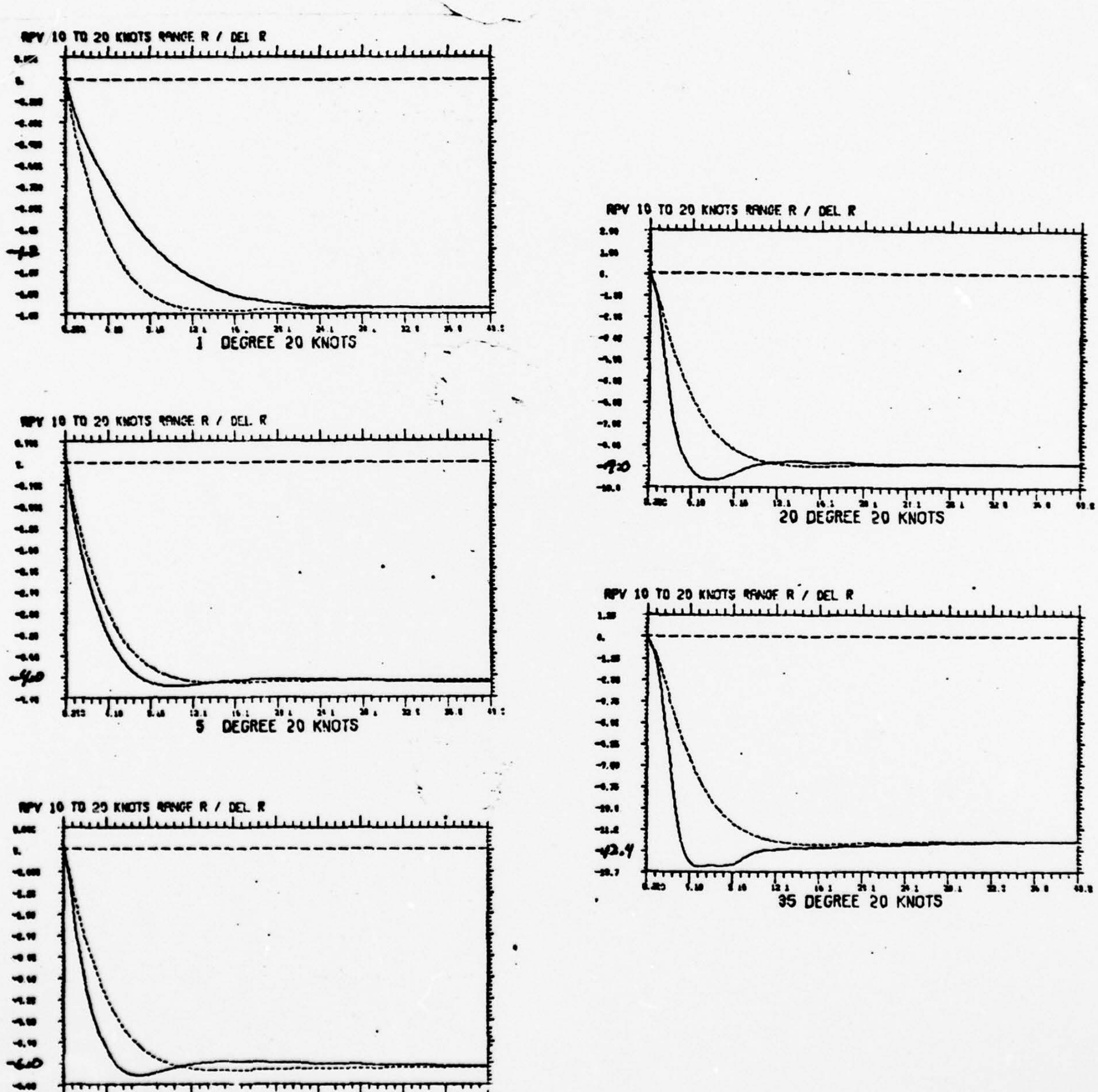
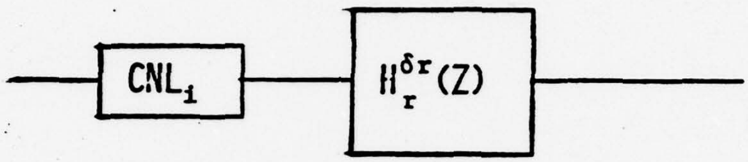


Fig. 52. R Versus δ_r, 20 Knots

Results of Validation Tests For: USF RPV

Transfer Function: R/δr

Model:



U_o: 25 Knots

U_-: 20 Knots

U_+: 30 Knots

$H_r^{\delta r}(Z)$ Determined Using U_o and 5° δr Step

$$H_r^{\delta r} = \frac{3.557 \times 10^{-2} Z - 2.615 \times 10^{-2}}{Z^2 - 1.854Z + 8.630 \times 10^{-1}}$$

Poles in the s Domain*

$-4.223 \times 10^{-1} \pm j\ 2.980 \times 10^{-1}$

*For conversion from Z-domain to S-domain, see references [11],[8].

Table 17

Custom nonlinearity (CNL): R versus δ_r

20-30 Knot range

δ_r	R steady state		
Degree	20 knots	25 knots	30 knots
0	0.00	0.00	0.00
1	-1.61	-1.98	-2.38
2	-2.40	-3.00	-3.60
3	-3.00	-3.80	-4.60
4	-3.60	-4.50	-5.40
5	-4.08	-5.14	-6.08
6	-4.55	-5.70	-6.65
7	-5.00	-6.10	-7.20
8	-5.40	-6.65	-7.70
9	-5.80	-7.10	-8.20
10	-6.14	-7.48	-8.60
11	-6.40	-7.80	-8.95
12	-6.70	-8.10	-9.30
13	-7.00	-8.40	-9.65
14	-7.20	-8.55	-10.00
15	-7.50	-9.00	-10.35
16	-7.80	-9.35	-10.70
17	-8.05	-9.65	-11.10
18	-8.35	-10.00	-11.40
19	-8.60	-10.30	-11.75
20	-8.90	-10.60	-12.10
21	-9.15	-10.90	-12.45
22	-9.30	-11.20	-12.80
23	-9.55	-11.45	-13.20
24	-9.75	-11.70	-13.55
25	-9.95	-12.00	-13.90
26	-10.15	-12.25	-14.25
27	-10.35	-12.55	-14.60
28	-10.55	-12.80	-15.00
29	-10.75	-13.05	-15.30
30	-11.00	-13.35	-15.70
31	-11.20	-13.60	-16.05
32	-11.40	-13.90	-16.40
33	-11.60	-14.15	-16.80
34	-11.80	-14.40	-17.15
35	-12.00	-14.70	-17.50
36	-12.20	-15.00	-17.85

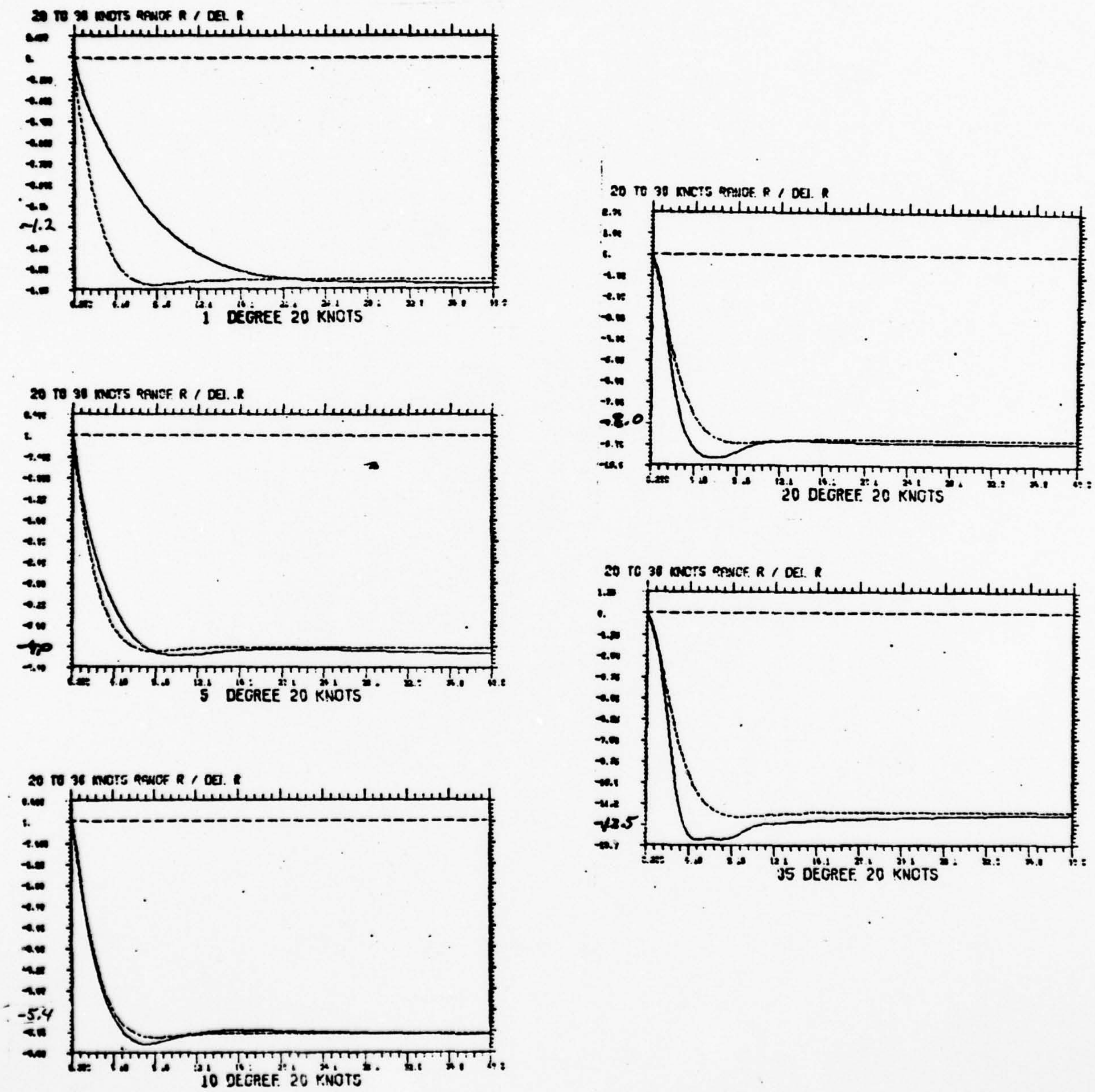


Fig. 53. R Versus δ_r, 20 Knots

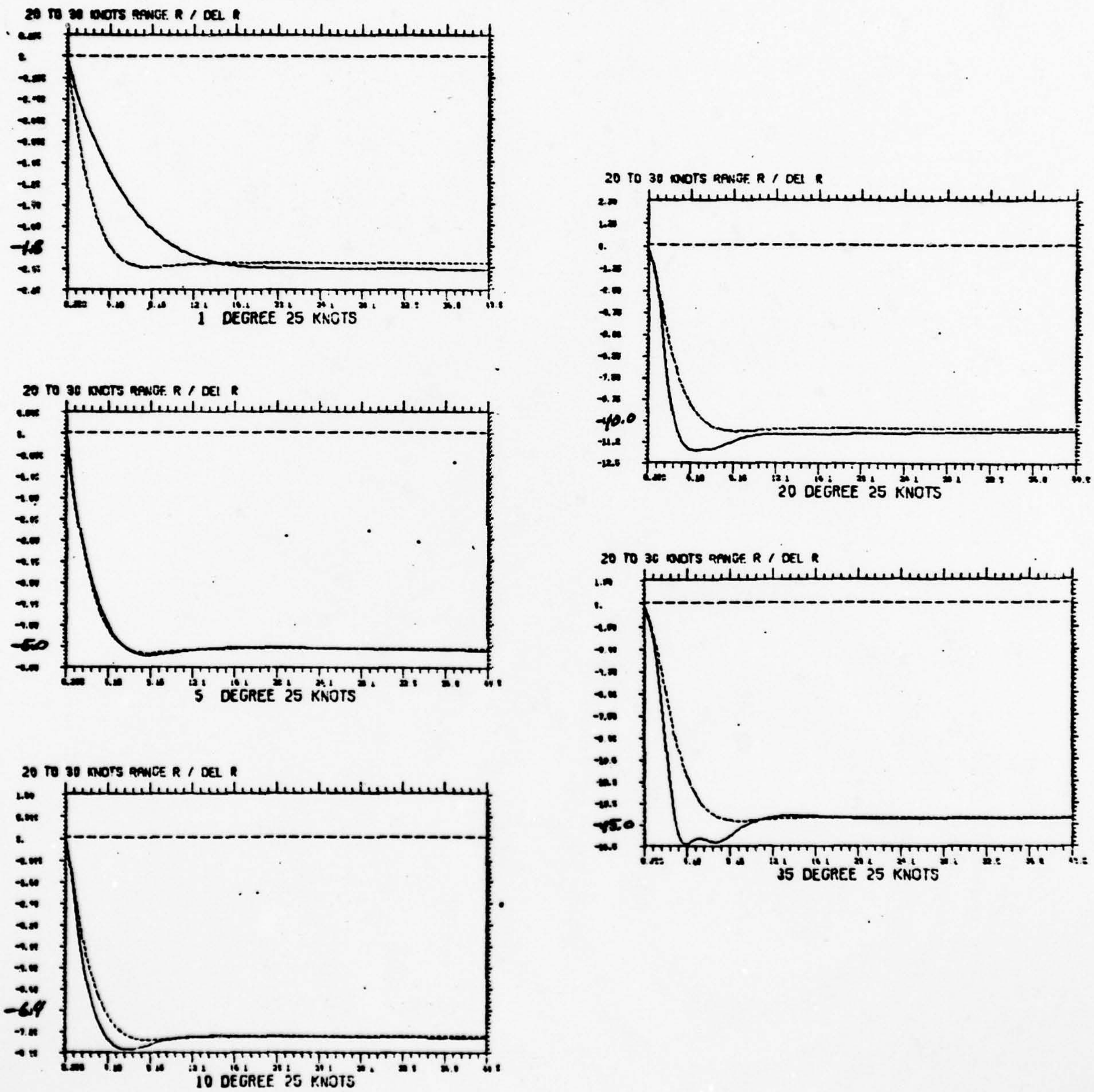


Fig. 54. R Versus δ_r, 25 Knots

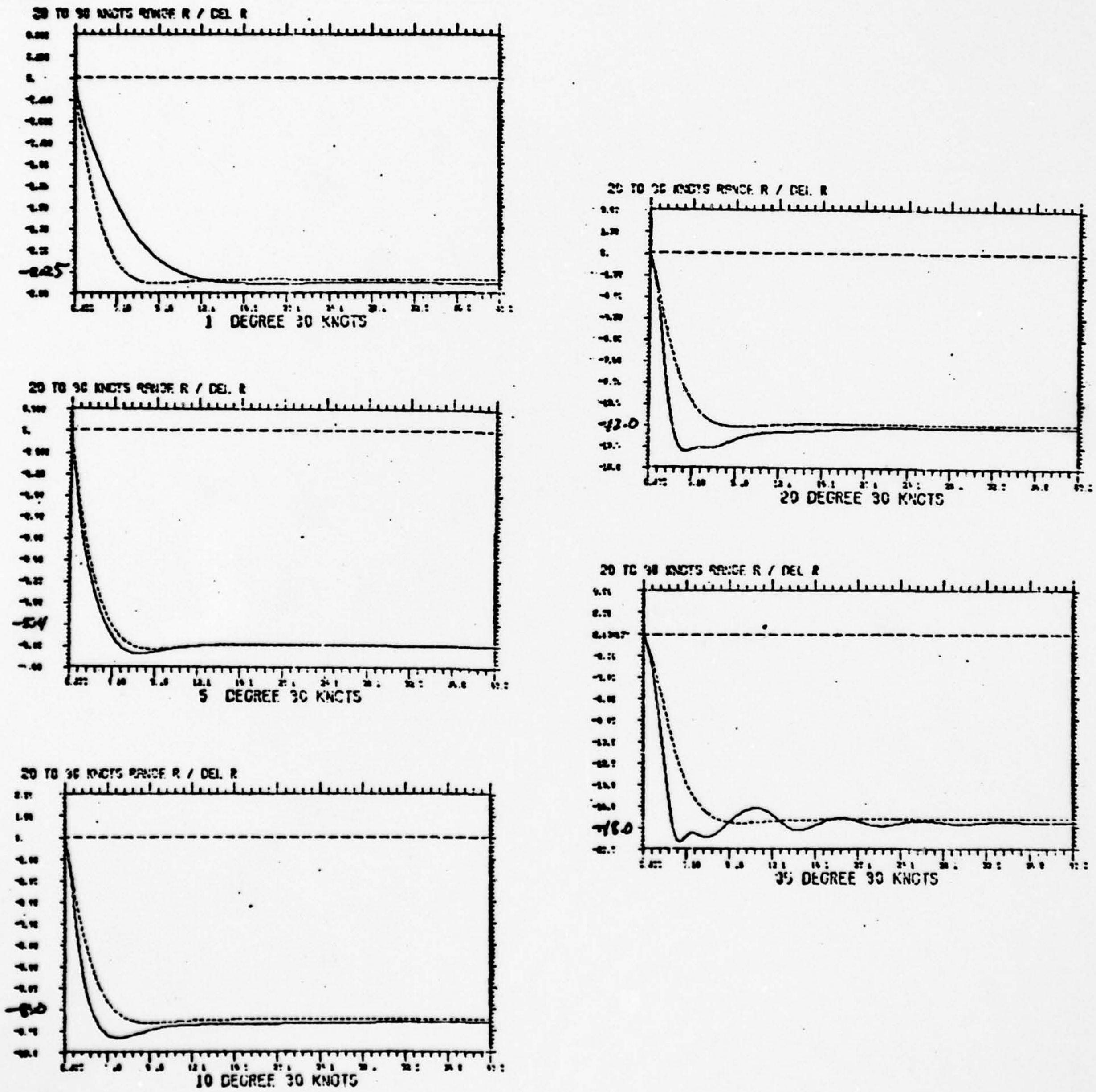


Fig. 55. R Versus δ_r, 30 Knots

AD-A064 604 UNIVERSITY OF SOUTH FLORIDA TAMPA DEPT OF ELECTRICAL--ETC F/G 13/10.1
NONLINEAR HANDLING CHARACTERISTICS MODELS FOR SUBMERGED VEHICLE--ETC(U)
OCT 78 V K JAIN, M K NICHOLS N61339-75-C-0122

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III. AMPLITUDE AND SPEED NORMALIZATION

In the equations of motion, the force term produced by a rudder deflection δ_r is proportionate to $\delta_r * U_o$ where U_o is the vehicle speed. It is therefore useful to normalize vehicle responses by a factor $C = \delta_r * U_o$ where U_o is in ft. per second. Such normalized responses are given in this section for the V and W variables. Fig. 56 to 58, Fig. 62 to 65 present a comparison of V and W responses, respectively, to various amplitude steps, each figure drawn for a fixed speed.

Also, it is known from principles of hydrodynamics that the responses of a submerged vehicle involves a time-scale factor which is directly proportional to speed. Specifically, this means the following. If the transfer function of a particular response variable, say side-slip, is $H(s_1)$ at a forward speed U_{01}, and it is $H(s_2)$ at another value of forward speed, U_{02}, then

$$t_2 = \frac{U_{01}}{U_{02}} t_1$$

$$s_2 = \frac{U_{02}}{U_{01}} s_1 \quad .$$

Clearly, a time normalization must be performed if the transient behavior at two different speeds are to be compared. This, of course, will be in addition to the amplitude normalization discussed above.

Fig. 59 to 61, Fig. 66 to 68 give comparison of amplitude and time normalized V and W, respectively, responses at various speeds, each figure drawn for a fixed amplitude rudder step.

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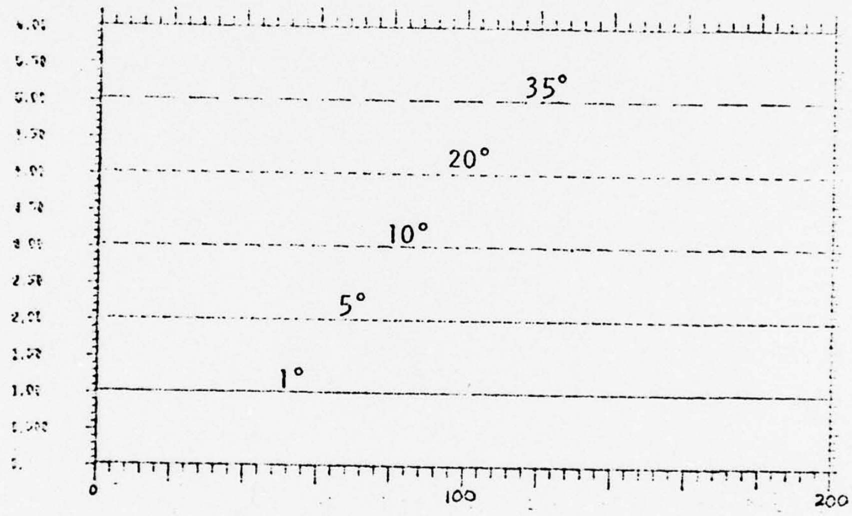

Key To Constant Speed Plots

Fig. 56

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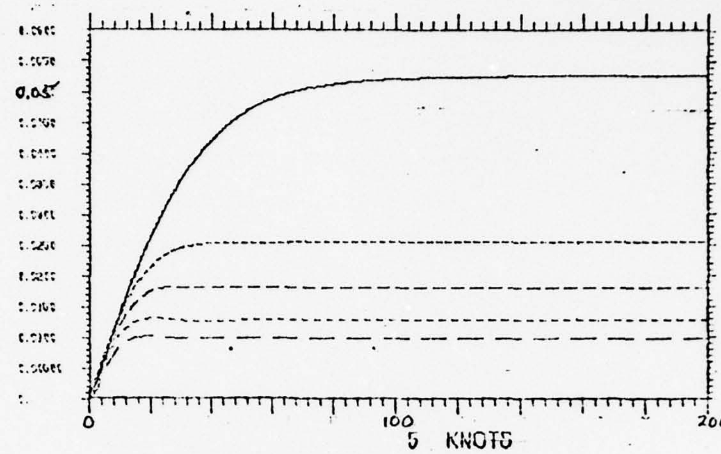

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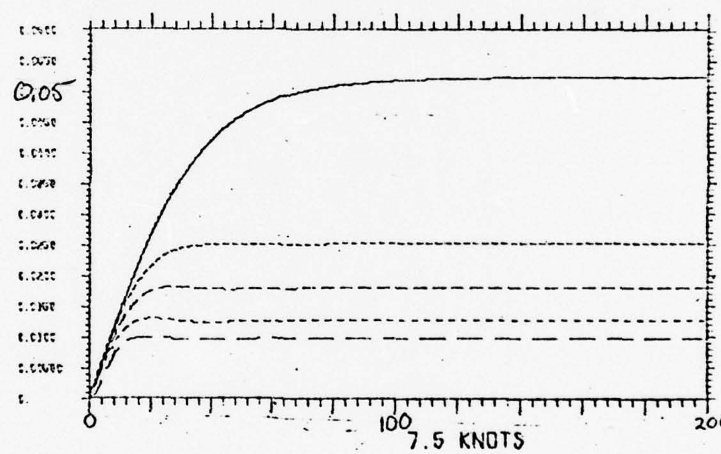

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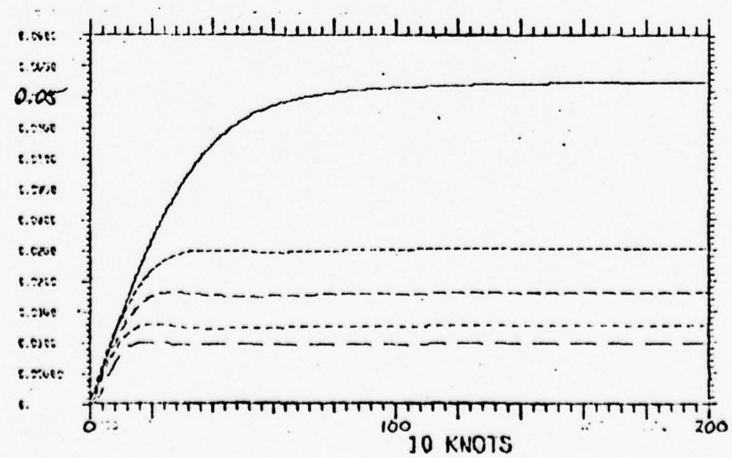

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Fig. 57

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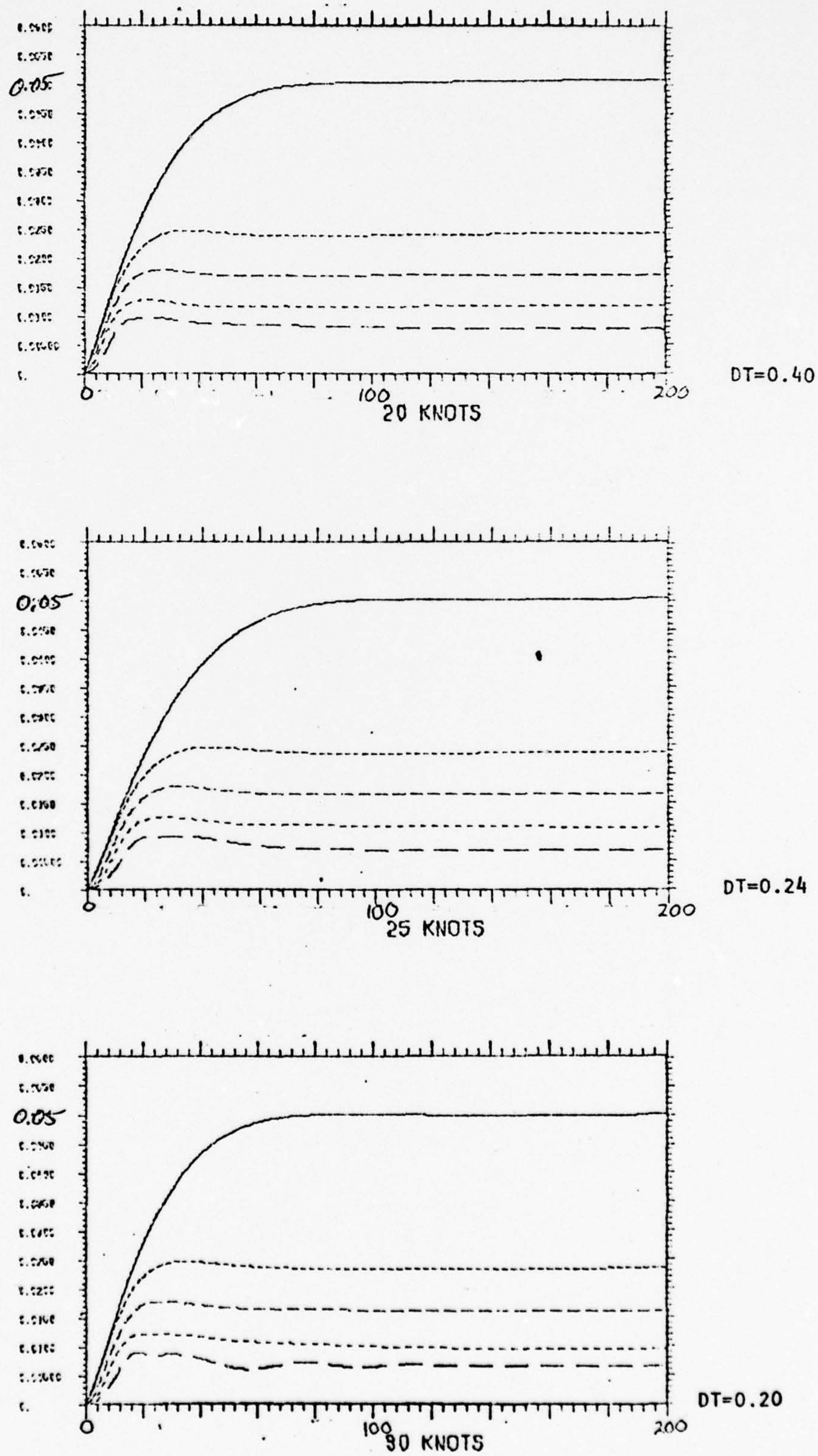

Fig. 58

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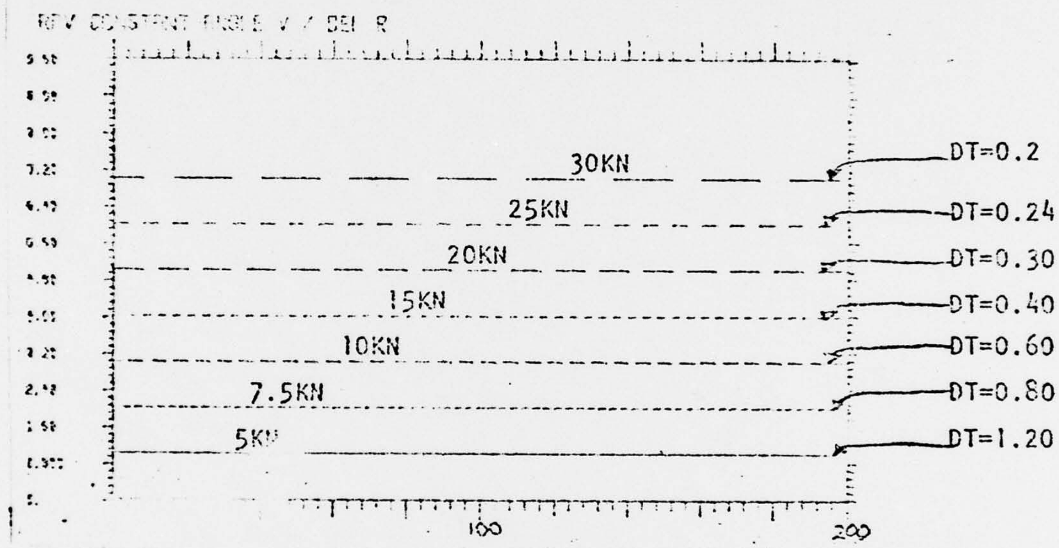

Key To Constant Angle Plots

Fig. 59

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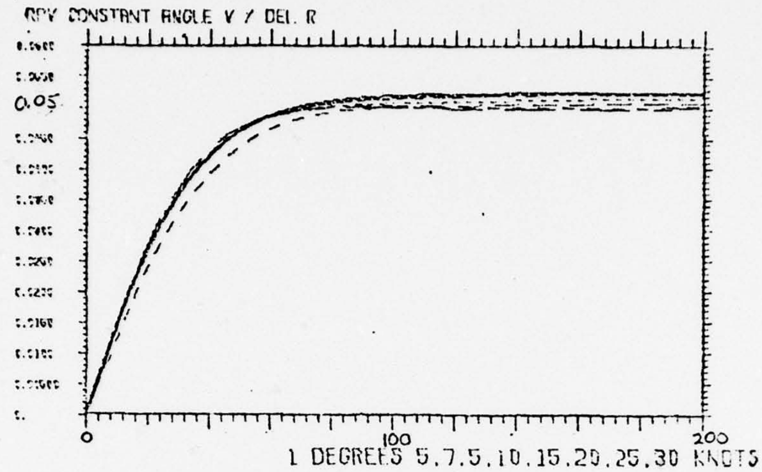

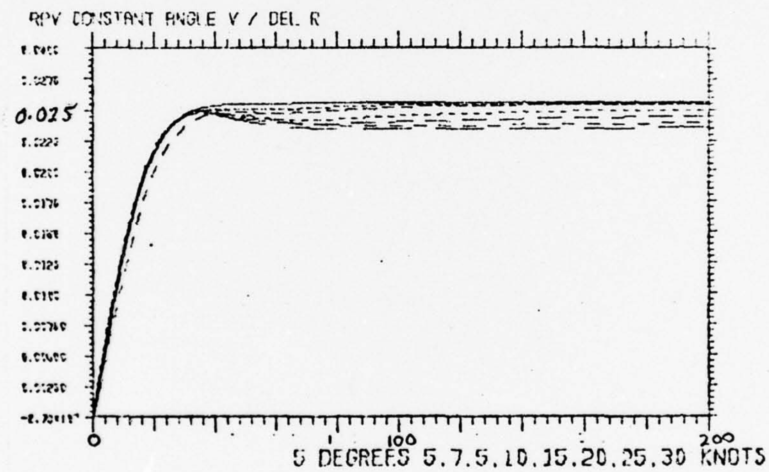

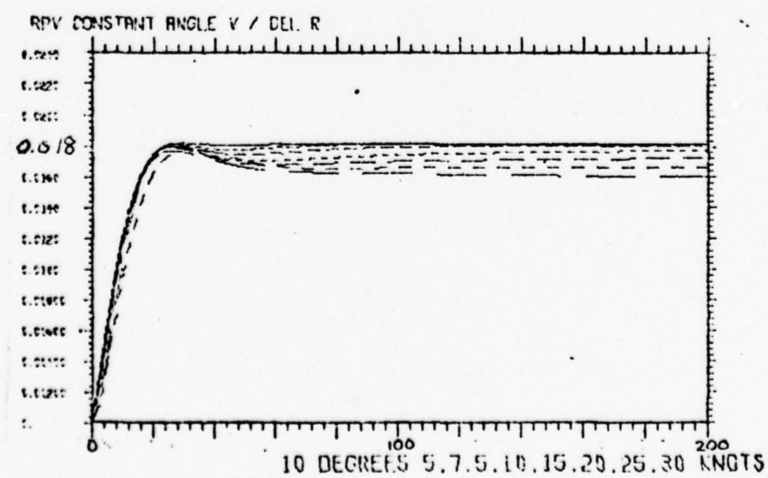

Fig. 60

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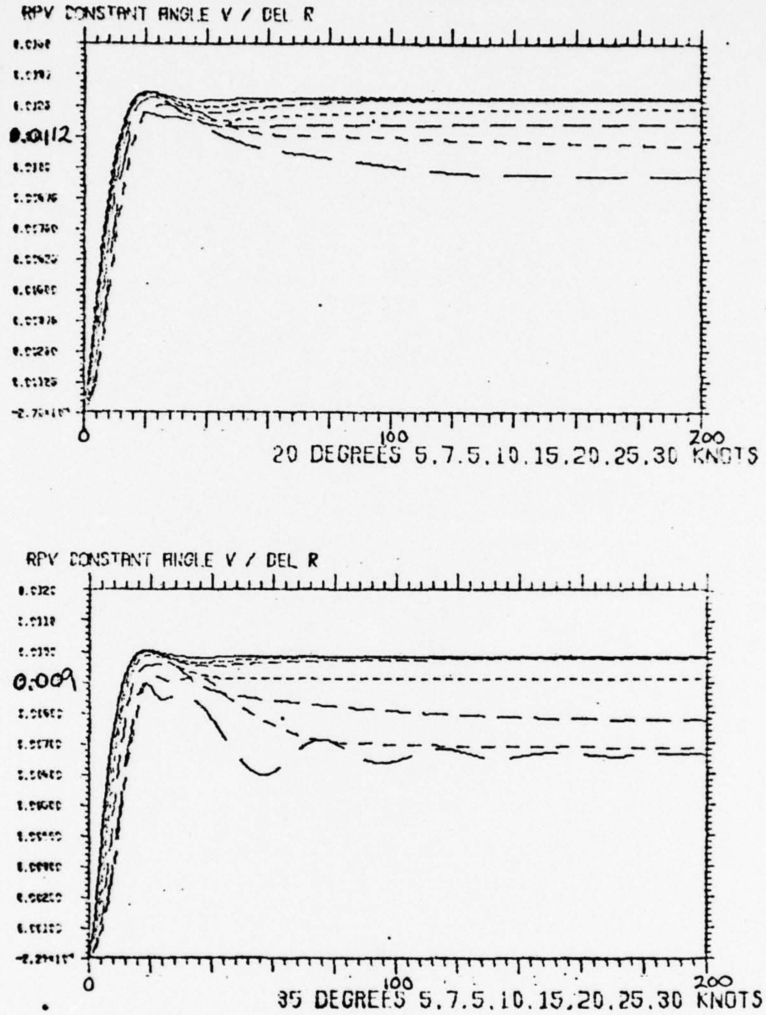

Fig. 61

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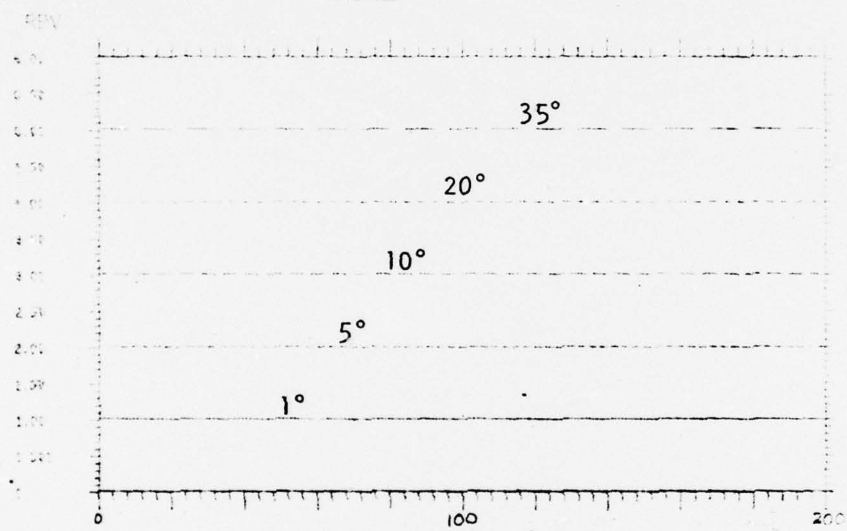

Key To Constant Speed Plots

Fig. 62

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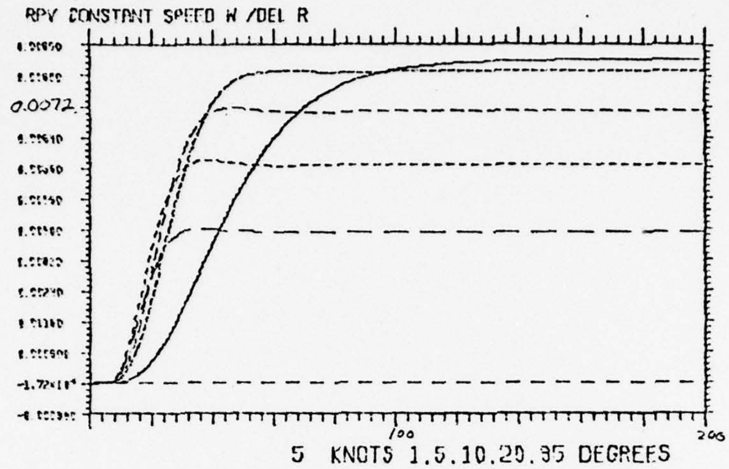

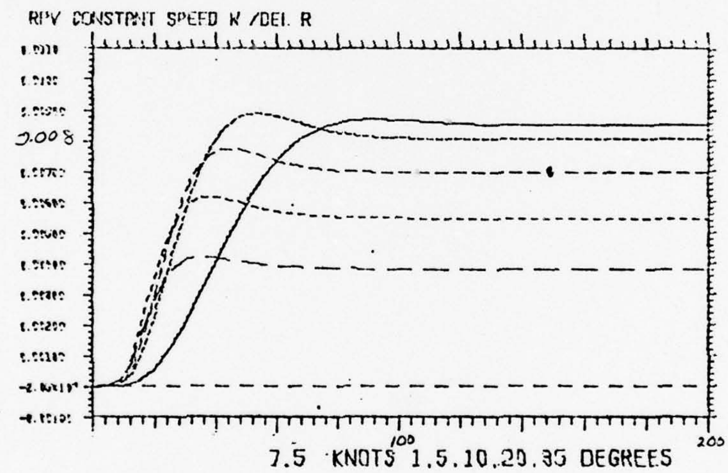

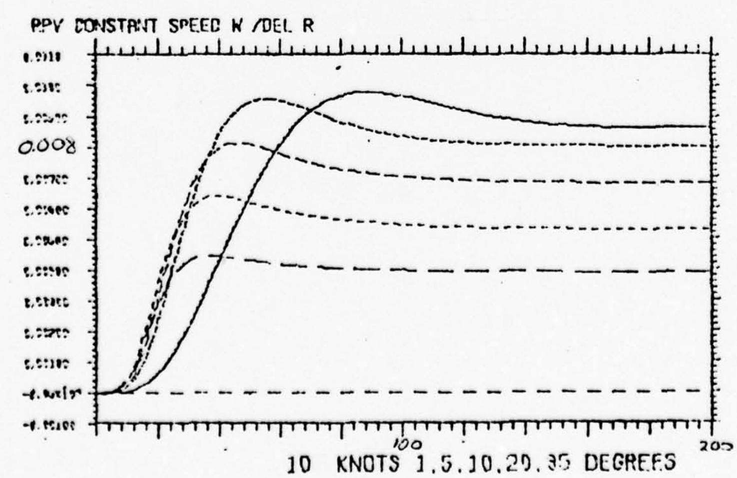

Fig. 63

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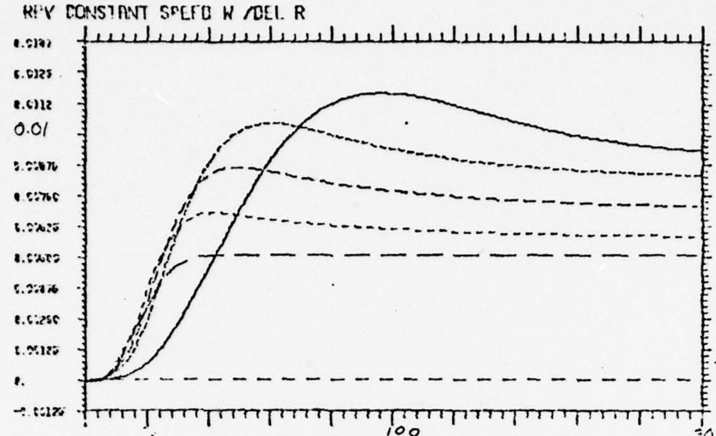
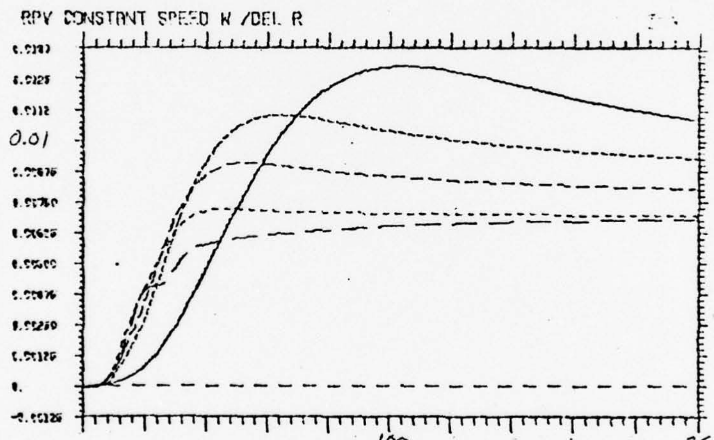
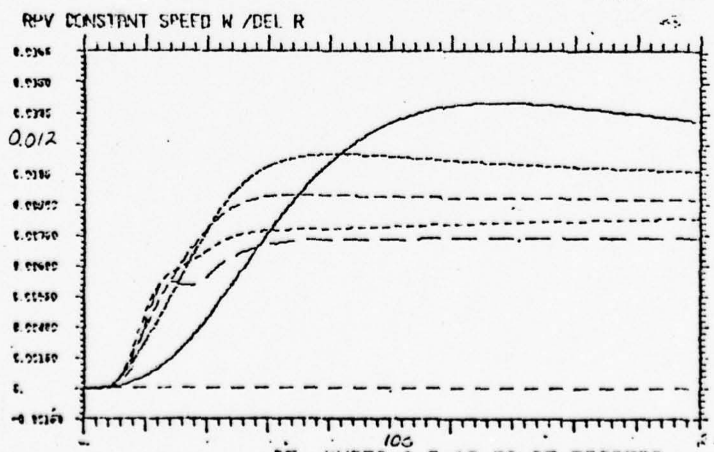


15 KNOTS 1,5,10,20,35 DEGREES



20 KNOTS 1,5,10,20,35 DEGREES



25 KNOTS 1,5,10,20,35 DEGREES

Fig. 64

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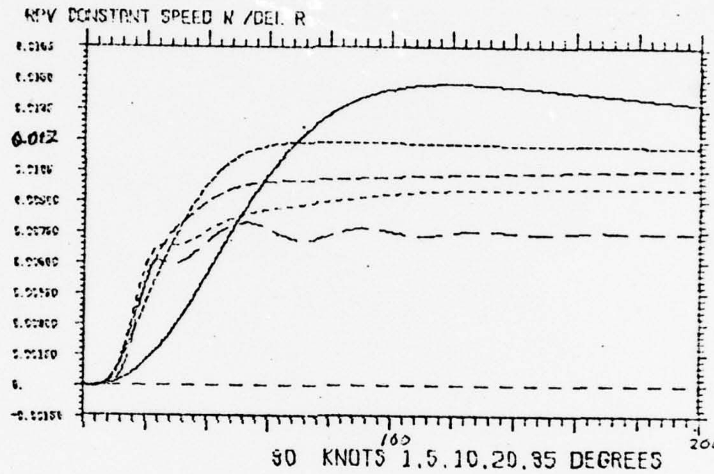

Fig. 65

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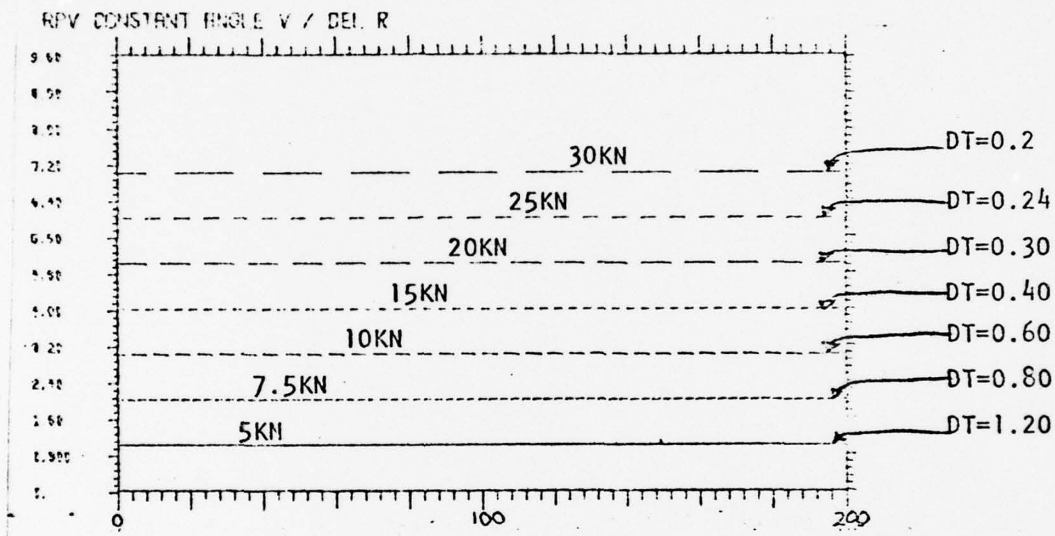

Key to Constant Angle Plots

Fig. 66

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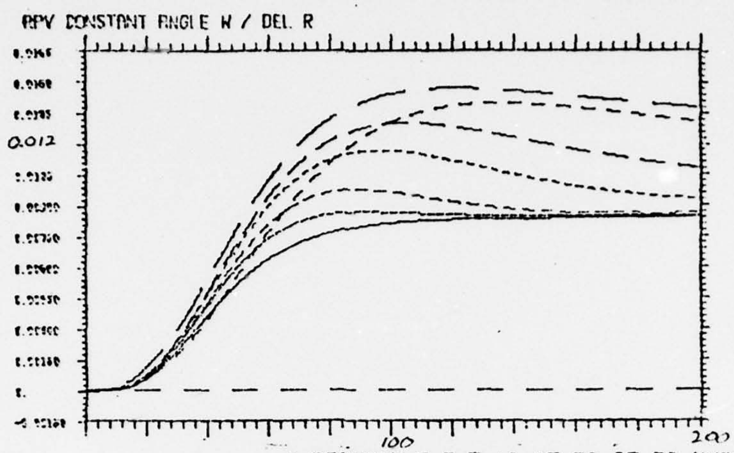
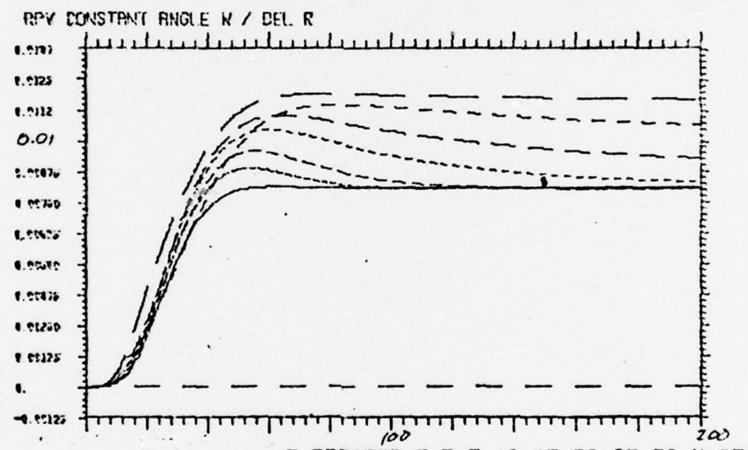
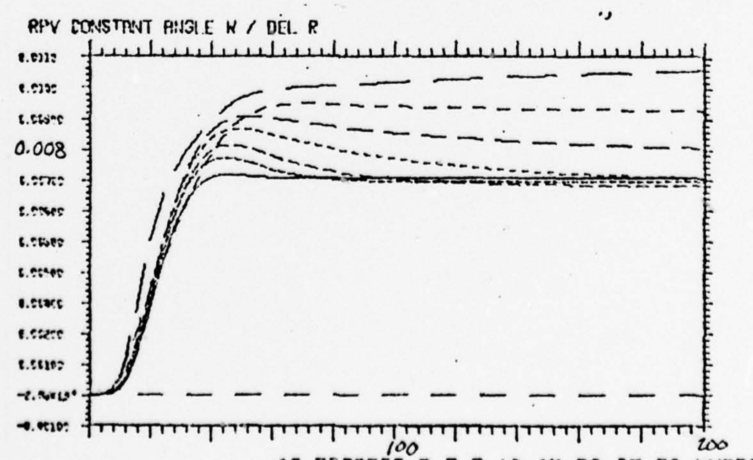


1 DEGREES 5.7.5.10.15.20.25.30 KNOT



5 DEGREES 5.7.5.10.15.20.25.30 KNOTS



10 DEGREES 5.7.5.10.15.20.25.30 KNOTS

Fig. 67

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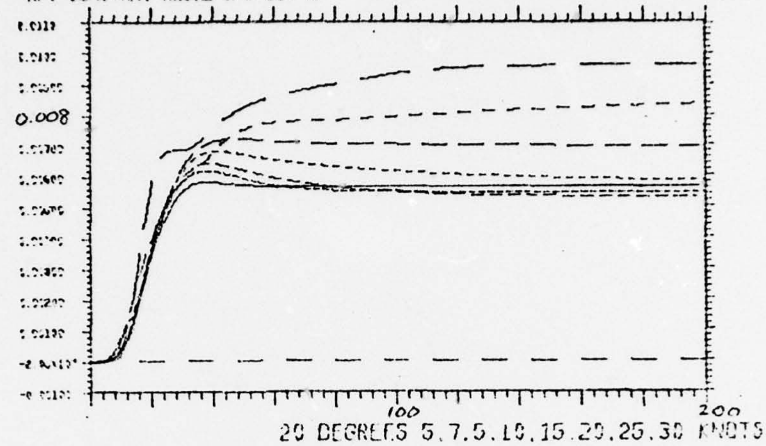

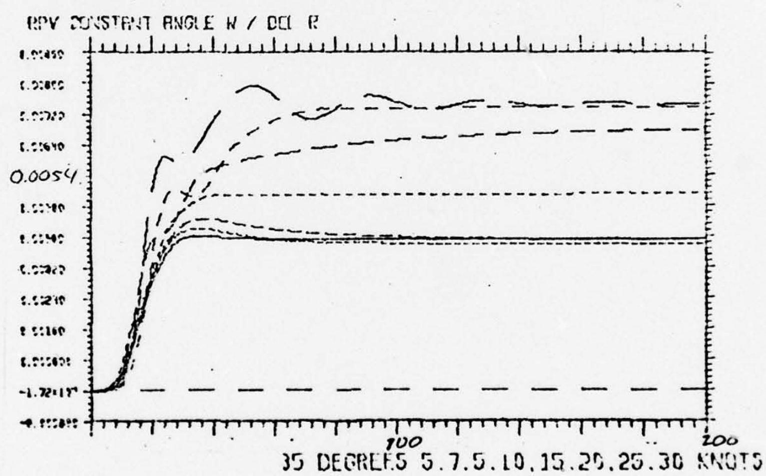

Fig. 68

IV. CNL NORMALIZATION OF RESPONSES

It was demonstrated in Section II that the vehicle responses bear a nonlinear relationship to the amplitude of the rudder input. In particular the steady state gain, for example $H_v(0) = V(\infty)/\delta_r$ for step-slide to a step rudder, exhibits a saturation behavior. In order to compare the transient modes at various rudder amplitudes, we must remove the effect of nonlinear gain H(0). Thus, we must determine CNL normalized responses by dividing the amplitude normalized response by a CNL gain reduction factor at the particular rudder deflection. For example,

$$\bar{v}(t) = \frac{v^*(t)}{f(\delta_r)}$$

$$= \frac{v(t)}{f(\delta_r)*\delta_r*U_0}$$

where $\bar{v}(t)$ denotes the CNL normalized response and

$$f(\delta_r) = \frac{\text{CNL gain at } \delta_r}{\text{CNL gain at } 1^\circ \text{ rudder}}$$

Also, of course, time normalization as discussed in Section III (p. 91) must be performed if transient response at different speeds are to be compared. That is, if $v(t_1)$ and $v(t_2)$ represent V and W responses at two different vehicle speeds, U_{01} and U_{02}, respectively, then

$$t_2 = \frac{U_{01}}{U_{02}} t_1$$

Fig. 69 to 72, Fig. 73 to 76 illustrate the effects of CNL Normalization on the transient response for V and W responses, respectively.

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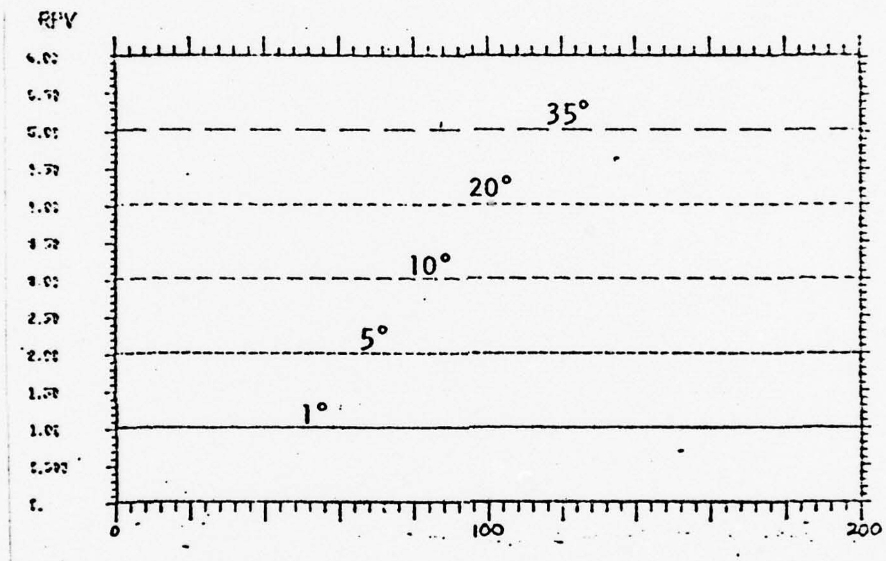

Key To Constant Speed Plots

Fig. 69

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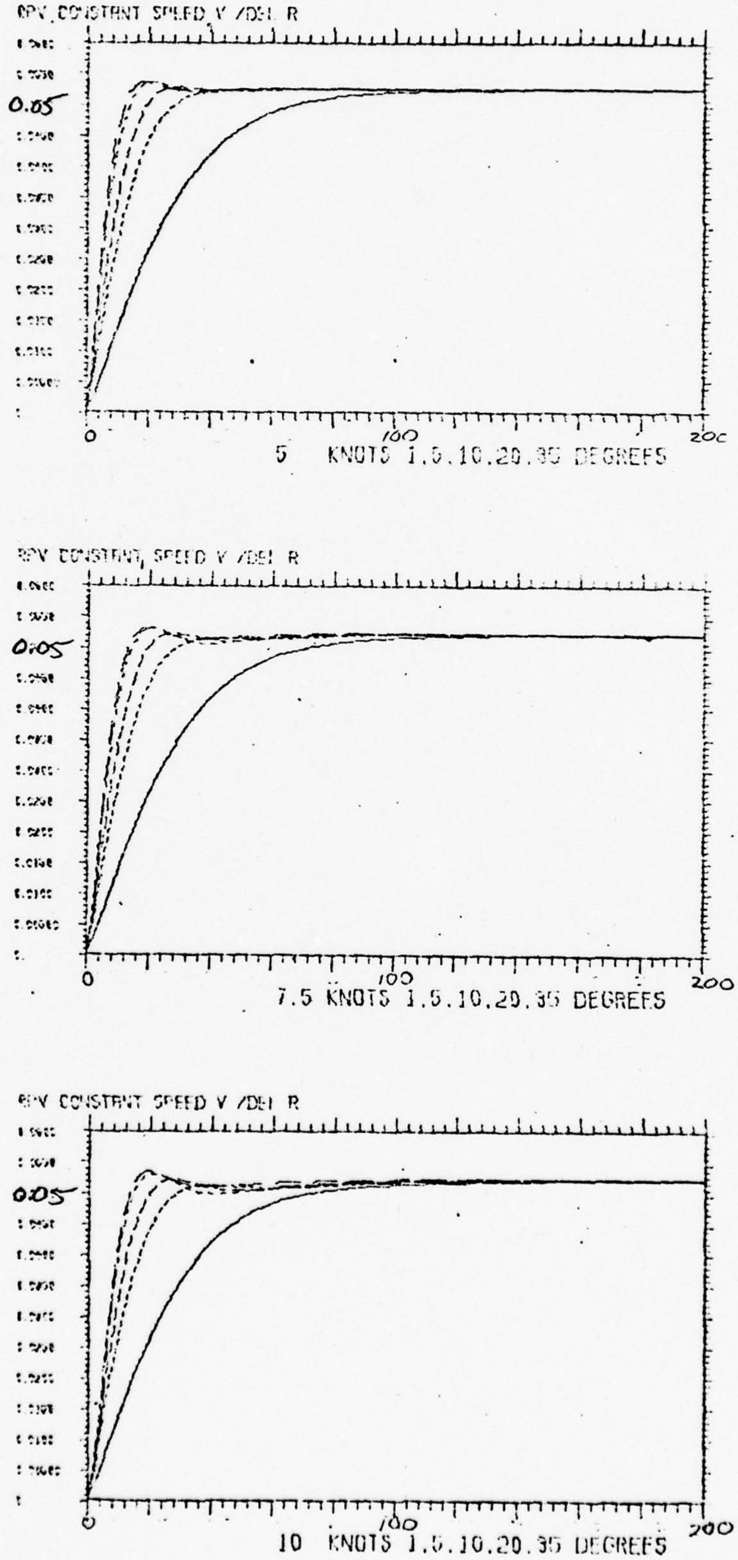

Fig. 70

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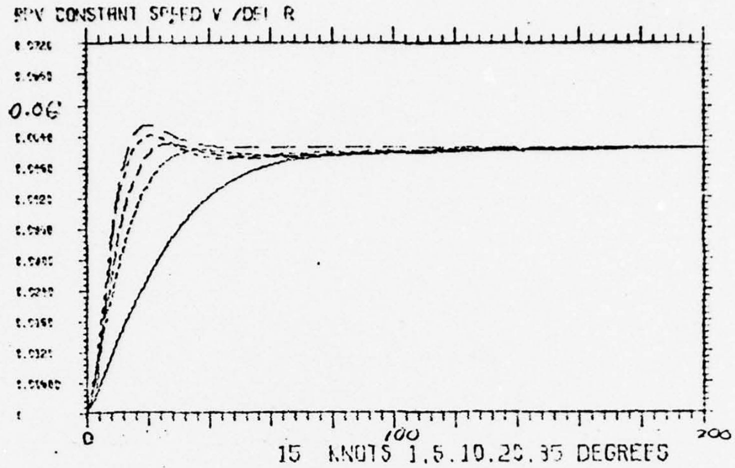

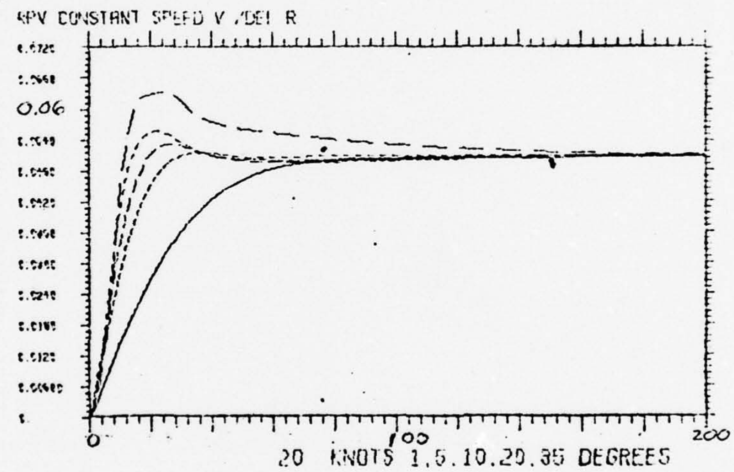

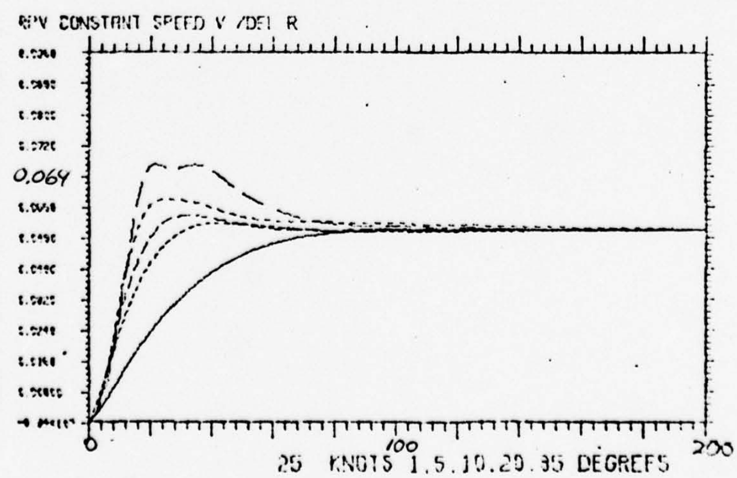

Fig. 71

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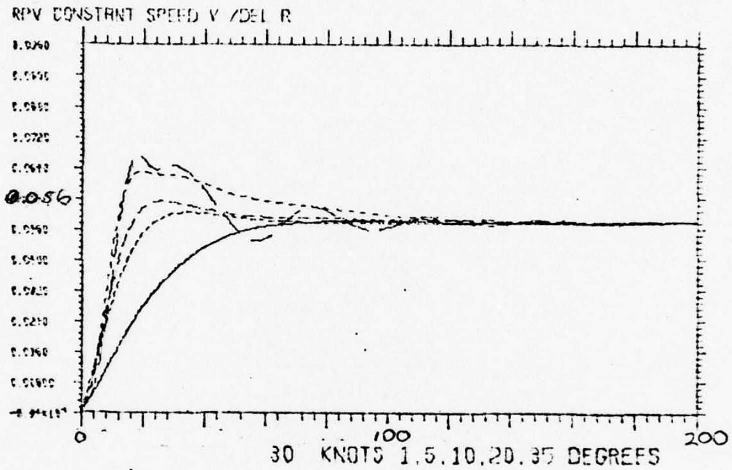

Fig. 72

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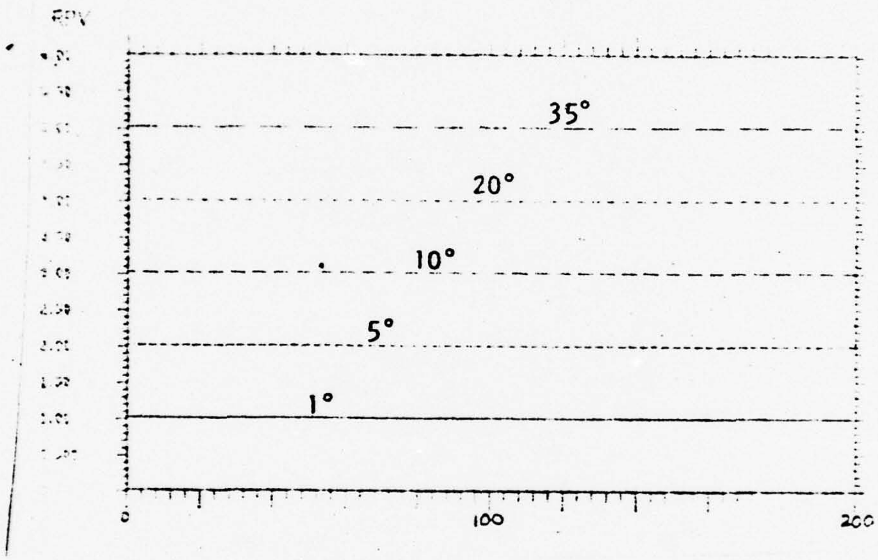

Key To Constant Speed Plots

Fig. 73

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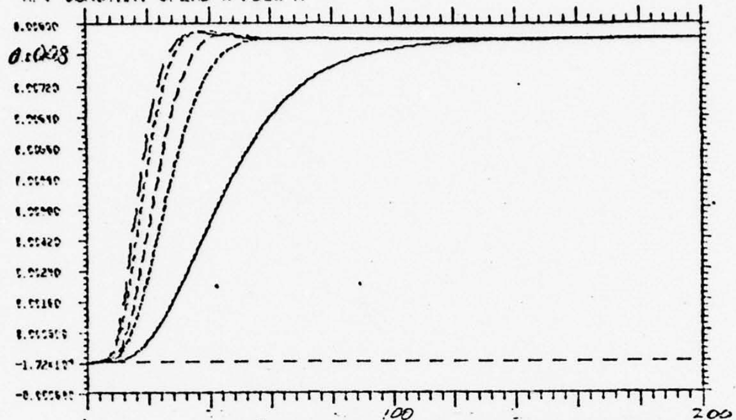
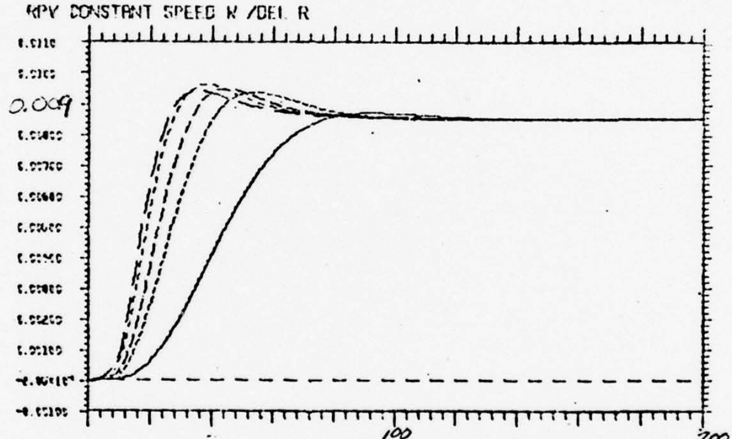
RPV CONSTANT SPEED R /DEL R



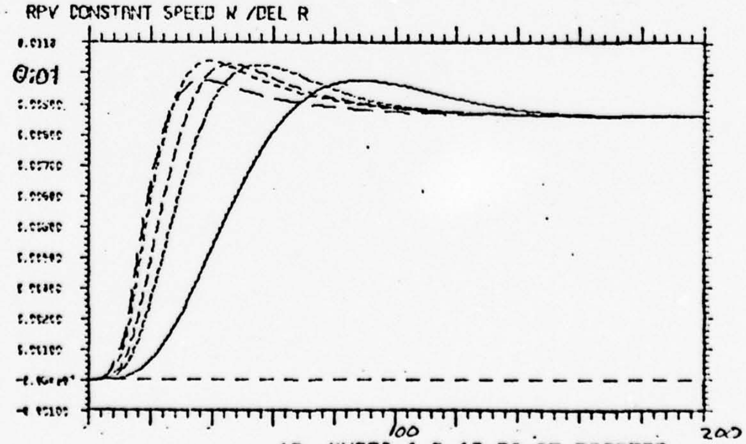
5 KNOTS 1.5.10.20.35 DEGREES

RPV CONSTANT SPEED R /DEL R



7.5 KNOTS 1.5.10.20.35 DEGREES

RPV CONSTANT SPEED R /DEL R



10 KNOTS 1.5.10.20.35 DEGREES

Fig. 74

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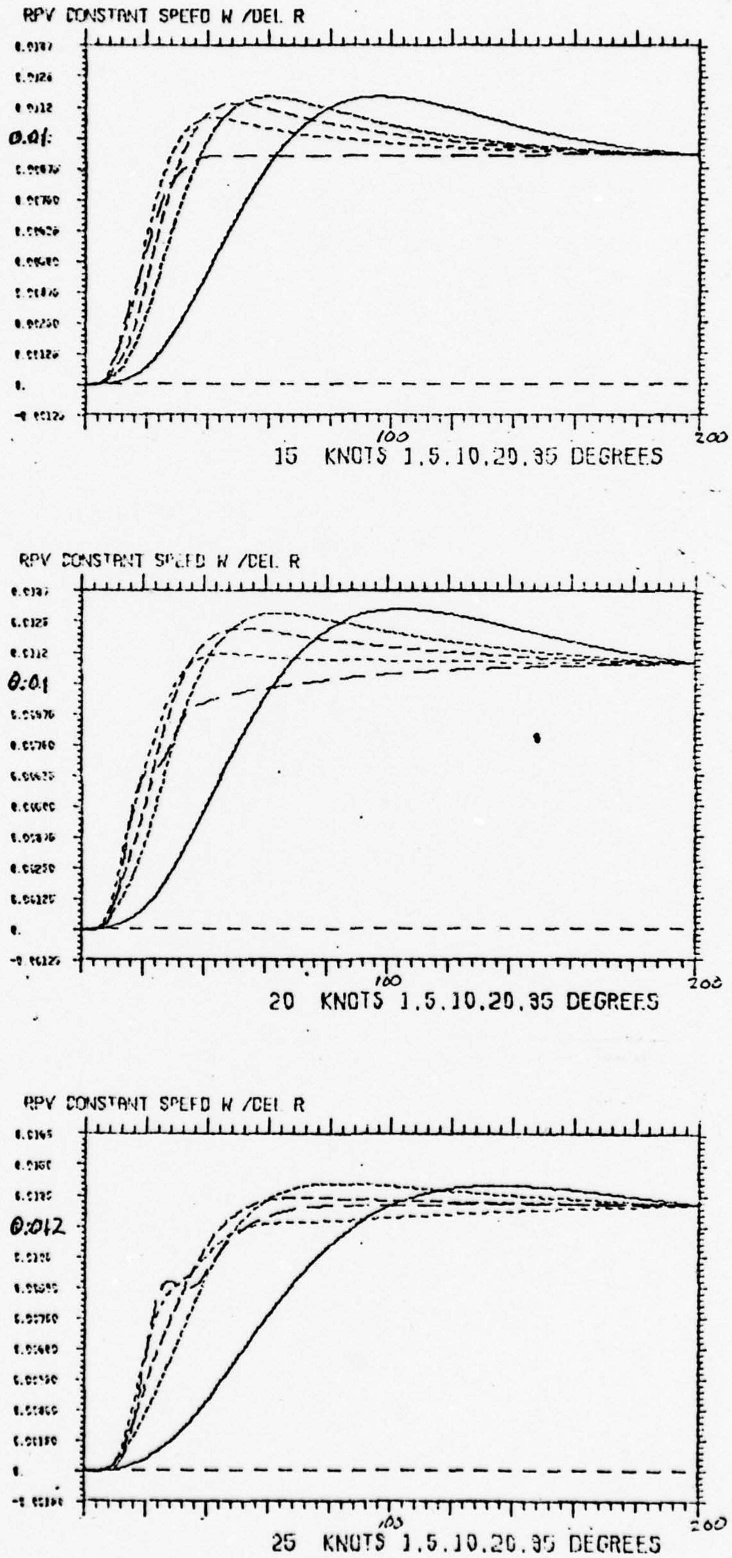

Fig. 75

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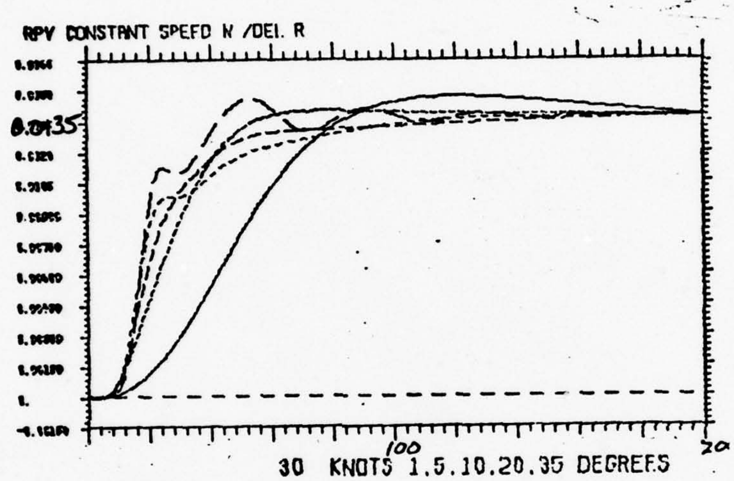

Fig. 76

V. PARAMETRIZATION OF TRANSFER FUNCTIONS

The undimensionalized force/moment input in the equation of motion is

$$\mu = \delta_r * U_o$$

so that the vehicle characterization can be expected to be different for various values of μ (in spite of the use of CNL). Even for a fixed speed the characterization, in particular H(s), can be expected to deviate from one nominal function. To surmount this problem we propose to parameterize the coefficients of H in terms of μ; or, at a fixed speed, in terms of δ_r. In this section we will deal with constant speed characterization.

To advoid this problem of incompatible transfer functions, a different strategy was needed in which the coefficients of the basic second order transfer functions were varied. Advoiding the need to generate transfer functions at all rudder inputs applied to the vehicle, we chose transfer function coefficient parametrization as the practical approach to the problem. From the basic transfer function configuration

$$H(s) = \frac{cs + b^*}{s^2 + as + b}$$

it can be observed that we need to parametrize a, b and c in terms of δ_r. (From the transfer functions in Tables and , it can be seen that b* is approximately b, thereby reducing the number of equations required).

The parameterization equations were determined for response variables V and W at speeds of 7.5, 15 and 25 knots. At each speed, s domain transfer functions were determined with step rudder inputs of 1°, 5°, 10°, 20° and 35°. These transfer functions are shown in Tables 19 and 20. We decided to parametrize a, b and c in the form

$$\hat{a} = \alpha_a + \beta_a(\delta_r) + \gamma_a(\delta_r)^2$$

$$\hat{b} = \alpha_b + \beta_b(\delta_r) + \gamma_b(\delta_r)^2$$

$$\hat{c} = \alpha_c + \beta_c(\delta_r) + \gamma_c(\delta_r)^2$$

The coefficients, α, β, γ are determined using the least squares technique. Consider, for example, the parametrization of a. The equations are:

$$a_{1^\circ} = \alpha + \beta(1^\circ) + \gamma\,(1^\circ)^2$$

$$a_{5^\circ} = \alpha + \beta(5^\circ) + \gamma\,(5^\circ)^2$$

$$a_{10^\circ} = \alpha + \beta(10^\circ) + \gamma(10^\circ)^2$$

$$a_{20^\circ} = \alpha + \beta(20^\circ) + \gamma(20^\circ)^2$$

$$a_{35^\circ} = \alpha + \beta(35^\circ) + \gamma(35^\circ)^2$$

or in matrix form

$$\underline{a} = X\,\underline{\theta}$$

where $\underline{\theta} = [\alpha, \beta, \gamma]^T$. By the least squares technique,[10]

$$\underline{\theta} = (X^T\,W^{-1}\,X)^{-1}\,X\,W^{-1}\,\underline{a}$$

where W is the weighting matrix W = Diag{1, 4, 9, 16, 25}

In Table 21 thru 26, the parametrization equations are given along with a comparison of parametrized coefficients ($\hat{a}$, $\hat{b}$, $\hat{c}$) to the transfer function coefficients at various rudder deflections.

TABLE 19

V Transfer Functions

δr	7.5 Knots	15 Knots	25 Knots
1°	$H(s) = \frac{0.307s + 0.0104}{s^2 + 0.218s + 0.088}$	$H(s) = \frac{0.0604s + 0.0267}{s^2 + 0.310s + 0.0266}$	$H(s) = \frac{0.103s + 0.0757}{s^2 + 0.500s + 0.0752}$
5°	$H(s) = \frac{0.0523s + 0.0227}{s^2 + 0.250s + 0.0229}$	$H(s) = \frac{0.0983s + 0.095}{s^2 + 0.489s + 0.0958}$	$H(s) = \frac{0.164s + 0.254}{s^2 + 0.737s + 0.254}$
10°	$H(s) = \frac{0.0609s + 0.0396}{s^2 + 0.307s + 0.0398}$	$H(s) = \frac{0.0896s + 0.166}{s^2 + 0.596s + 0.169}$	$H(s) = \frac{0.204s + 0.341}{s^2 + 0.743s + 0.340}$
20°	$H(s) = \frac{0.0686s + 0.065}{s^2 + 0.365s + 0.653}$	$H(s) = \frac{0.0663s + 0.264}{s^2 + 0.673s + 0.267}$	$H(s) = \frac{0.467s + 0.186}{s^2 + 0.577s + 0.182}$
35°	$H(s) = \frac{0.0572s + 0.107}{s^2 + 0.491s + 0.107}$	$H(s) = \frac{0.160s + 0.243}{s^2 + 0.593s + 0.242}$	$H(s) = \frac{0.578s + 0.111}{s^2 + 0.450s + 0.110}$

TABLE 20

W Transfer Functions

δr	7.5 Knots	15 Knots	25 Knots
1°	$H(s) = \frac{-0.00458s \quad 0.00122}{s^2 - 0.0814s + 0.00763}$	$H(s) = \frac{-0.0163s + 0.00602}{s^2 + 0.0405s + 0.00904}$	$H(s) = \frac{-0.0393s + 0.0225}{s^2 + 0.169s + 0.0222}$
5°	$H(s) = \frac{-0.0132s + 0.00361}{s^2 - 0.0141s + 0.00853}$	$H(s) = \frac{-0.0557s + 0.0255}{s^2 + 0.169s + 0.0255}$	$H(s) = \frac{-0.0685s + 0.0714}{s^2 + 0.343s - 0.0691}$
10°	$H(s) \frac{-0.0230s + 0.0066}{s^2 + 0.315s + 0.0106}$	$H(s) = \frac{-0.076s + 0.0412}{s^2 + 0.227s + 0.0399}$	$H(s) = \frac{-0.105s + 0.126}{s^2 + 0.534s + 0.125}$
20°	$H(s) = \frac{-0.0374s + 0.0117}{s^2 + 0.0851s + 0.0145}$	$H(s) = \frac{-0.0896s + 0.0610}{s^2 + 0.294s + 0.0593}$	$H(s) = \frac{-0.349s + 0.358}{s^2 + 1.44s + 0.369}$
35°	$H(s) = \frac{-0.494s + 0.0171}{s^2 = 0.133s + 0.019}$	$H(s) = \frac{-0.1062s + 0.0861}{s^2 + 0.471s + 0.0883}$	$H(s) = \frac{-0.706s + 0.772}{s^2 + 2.883s + 0.771}$

TABLE 21

Variable: V

Speed: 7.5 Knots

Transfer Function in the Form:

$$H(s) = \frac{cs + b}{s^2 + as + b}$$

Parametrization Equations:

$$\hat{a} = 0.2091 + 0.0089\delta r - 0.00004\delta r^2$$

$$\hat{b} = 0.0057 + 0.0034\delta r - 0.00002\delta r^2$$

$$\hat{c} = 0.3275 - 0.0387\delta r + 0.00094\delta r^2$$

Comparison of Coefficients:

a - transfer function coefficient

$\hat{a}$ - parameterized coefficient

δr	a	$\hat{a}$	b	$\hat{b}$	c	$\hat{c}$
1°	0.307	0.290	0.009	0.009	0.218	0.218
5°	0.052	0.158	0.023	0.023	0.250	0.253
10°	0.061	0.034	0.04	0.039	0.307	0.295
20°	0.069	-0.071	0.065	0.068	0.365	0.375
35°	0.057	0.122	0.107	0.106	0.491	0.487

TABLE 22

Variable: V

Speed: 15

Transfer Function in the Form:

$$H(s) = \frac{cs + b}{s^2 + as + b}$$

Parameterization Equations:

$$\hat{a} = 0.27491 + 0.04141\delta r - 0.00094\delta r^2$$

$$\hat{b} = 0.00644 + 0.02038\delta r - 0.00039\delta r^2$$

$$\hat{c} = 0.06162 + 0.00262\delta r - 0.00001\delta r^2$$

Comparison of Coefficients:

a - transfer function coefficient

$\hat{a}$ - parameterized coefficient

δr	a	$\hat{a}$	b	$\hat{b}$	c	$\hat{c}$
1°	0.310	0.315	0.027	0.0264	0.06	0.0642
5°	0.489	0.458	0.096	0.0987	0.098	0.0745
10°	0.596	0.595	0.196	0.071	0.09	0.0868
20°	0.673	0.726	0.267	0.259	0.066	0.110
35°	0.593	0.570	0.242	0.245	0.160	0.141

TABLE 23

Variable: V

Speed: 25 Knots

Transfer Function in the Form:

$$H(s) = \frac{cs + b}{s^2 + as + b}$$

Parameterization Equations

$$\hat{a} = 0.48255 + 0.03646\delta r - 0.00113\delta r^2$$

$$\hat{b} = 0.5395 + 0.0337\delta r - 0.00097\delta r^2$$

$$\hat{c} = 0.08347 + 0.01711\delta r - 0.00007\delta r^2$$

Comparison of Coefficients

a - transfer function coefficient

â - parameterized coefficient

δr	a	$\hat{a}$	b	$\hat{b}$	c	$\hat{c}$
1°	0.500	0.518	0.0750	0.0867	0.103	0.101
5°	0.737	0.637	0.254	0.198	0.164	0.167
10°	0.743	0.734	0.340	0.294	0.204	0.248
20°	0.577	0.759	0.182	0.340	0.467	0.399
35°	0.450	0.372	0.110	0.0465	0.578	0.602

TABLE 24

Variable: W

Speed: 7.5 knots

Transfer Function in the Form

$$H(s) = \frac{cs + b}{s^2 + as + b}$$

Parameterization Equations

$$\hat{a} = -0.11588 + 0.03415\delta_r - 0.000081\delta_r^2$$

$$\hat{b} = 0.00721 + 0.00033\delta r + 0\delta_r^2$$

$$\hat{c} = -0.0028 - 0.002233\delta r + 0.000003\delta_r^2$$

Comparison of Coefficients

a - transfer function coefficient

$\hat{a}$ - parameterized coefficient

δ_r	a	$\hat{a}$	b	$\hat{b}$	c	$\hat{c}$
1°	-0.0814	-0.0825	0.0076	0.00754	-0.00458	-0.00458
5°	-0.0141	0.0346	0.0085	0.00887	-0.0132	-0.0132
10°	0.315	0.144	0.0106	0.0105	-0.023	-0.0228
20°	0.0851	0.242	0.0145	0.0140	-0.0374	-0.0376
35°	0.133	0.0852	0.019	0.0192	-0.0494	-0.0493

TABLE 25

Variable: W

Speed: 15 knots

Transfer Function in the Form:

$$H(s) = \frac{cs + b}{s^2 + as + b}$$

Parameterization Equations:

$$\hat{a} = 0.02412 + 0.02323\delta r - 0.00032\delta_r^2$$

$$\hat{b} = -0.0031 + 0.005\delta r - 0.0001\delta_r^2$$

$$\hat{c} = -0.0102 - 0.008\delta r + 0.0002\delta_r^2$$

Comparison of Coefficients:

a - transfer function coefficient

$\hat{a}$ - parameterized coefficient

δr	a	$\hat{a}$	b	$\hat{b}$	c	$\hat{c}$
1°	0.0405	0.0470	0.000904	0.0018	-0.0163	-0.018
5°	0.169	0.1322	0.0255	0.0202	-0.0557	-0.0463
10°	0.227	0.2242	0.0399	0.0398	-0.076	-0.0745
20°	0.294	0.3599	0.0593	0.0683	-0.0896	-0.108
35°	0.471	0.4426	0.0883	0.0843	-0.1062	-0.0985

TABLE 26

Variable: W

Speed: 25 Knots

Transfer Function in the Form:

$$H(s) = \frac{cs + b}{s^2 + as + b}$$

Parameterization Equations:

$$\hat{a} = 0.1300 + 0.0353\delta r + 0.0013\delta^2$$

$$\hat{b} = 0.00648 + 0.00062\delta r + 0.00064\delta_r^2$$

$$\hat{c} = -0.03133 - 0.00604\delta r - 0.00039\delta_r^2$$

Comparison of Coefficients:

a - transfer function coefficient

â - parameterized coefficient

δr	a	â	b	$\hat{b}$	c	ĉ
1°	0.169	0.167	0.0222	0.00775	-0.0394	-0.0378
5°	0.343	0.338	-0.0691	0.0257	-0.0685	-0.0713
10°	0.534	0.610	0.125	0.0771	-0.105	-0.131
20°	1.44	1.34	0.369	0.277	-0.349	-0.308
35°	2.88	2.91	0.771	0.817	-0.706	-0.721

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APPENDIX A

Listing of Program VERIFY

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```
//STEPZ EXEC FTG1CLG,LIB5='USF.IR.PLOTLIB'
//FORT.SYSIN DD *
C
C
C     PROGRAM VERIFY
C     SIMULATES A SINGLE INPUT - SINGLE OUTPUT CNL + H(Z) CASCODE
C     COMPARES THE RESPONSE WITH NCSL PROGRAM TRAJECTORY
C
C
      DIMENSION X(200,15),Y(200,15),YREC(200,15),YPLOT(200,3),
     A NAMEM(15,15),NMAIO(15,15),UNL( 37),BUFF(200,4),SP(10),
     B TITLE(80)
      REAL*8 GAMMA(20),DELTA,GAIN,GAMMA1(20,8)
      REAL*8 XLAMDA(20)
      WRITE(6,202)
      READ(5,1)N,NMOD,IXX,IYY,DELTA
      WRITE(6,11)NMOD,N
      WRITE(6,203)
      NP1=N+1
      NP2=N+2
      NPNP1=N+N+1
      NPNP2=N+N+2
C
C
C     READ ALL H(Z) MODELS ( E. G., FOR THREE DIFFERENT SPEEDS, 10,15,20
C
      DO 199 J=1,NMOD
      READ(5,015)(NAMEM(I,J),I=1,15)
      READ(5,2)   (GAMMA(I),I=1,NP1)
      WRITE(6,4)
      CALL PRVEC(GAMMA(1),NP1)
      READ(5,2)   (GAMMA(I),I=NP2,NPNP2)
      WRITE(6,5)
      CALL PRVEC(GAMMA(NP2),NP1)
      DO546I=NP2,NPNP2
546   GAMMA(I)=-GAMMA(I)
      DO 199 I=1,NPNP2
199   GAMMA1(I,J)=GAMMA(I)
C     READ CNL AND PLOT OPTIONS, AND CNL TABLE
      READ(5,1) ICNL ,IPLOT,IDYN
      WRITE(6,12) ICNL,IPLOT,IDYN
      IF(ICNL.NE.0)READ(5,9)(UNL(K),K=1,37)
C     READ NUMBER OF MANUEVERS (FOR EACH MODEL),THEIR TITLES,
C     THEIR DATA,AND NCSL TRAJECTORIES;IF DESIRED
C     APPLY CNL TO INPUT
      READ(5,1)MNVR
      WRITE(6,13)MNVR
      DO 112 J=1,MNVR
118   READ(5,6,END=116)NPT,(NMAIO(I,J),I=1,15)
      READ(5,201) TITLE
      READ(5,6889) (X(K,J),K=1,NPT)
      IF(ICNL.NE.0) CALL NONLT(X(1,J),UNL,NPT)
      READ(5,201) TITLE
      READ(5,6889)(Y(K,J),K=1,NPT)
112   CONTINUE
```

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```
          DO 113 K=1,NPT
    113   YPLOT(K,3)=0.0
C
C         VERIFY EACH MODEL; FOR EACH MANEUVER
C
C
C
          DO 116 M=1,NMOD
          WRITE(6,415)(NAMEM(I,M),I=1,15)
          WRITE(6,204)
          DO 115 J=1,MNVR
          WRITE(6,416)(NMAIO(I,J),I=1,15)
          CALL RESPON(YREC(1,J),X(1,J),N,GAMMA1(1,M),XLAMDA,NPT)
C         COMPARE Y AND YREC. CAL RMS ERROR + %RMS ERROR
          SUM=0.0
          DO 105 K=1,NPT
    105   SUM=SUM+YREC(K,J)*YREC(K,J)
          RMS=SQRT(SUM/NPT)
          SUM=0.0
          SUMW=0.0
          I=J
          DO111 K=1,NPT
          YPLOT(K,1)=Y(K,I)
          YPLOT(K,2)=YREC(K,I)
          SUMW=SUMW+Y(K,I)*Y(K,I)
    111   SUM=SUM+(Y(K,I)-YREC(K,I))*(Y(K,I)-YREC(K,I))
          RMS=SQRT(SUM/NPT)
          RMSW=SQRT(SUMW/NPT)
          PC=100.*RMS/RMSW
          WRITE(6,48) I,RMS,PC
          IF(IPLOT.NE.0)CALL PLOP8(NPT,3,YPLOT,200,.2,.2,5,NAMEM(1,M),
        * NMAIO(1,J),BUFF)
    115   CONTINUE
    116   CONTINUE
          CALL PICSIZ(0.0,0.0)
    1     FORMAT(4I5,F10.0)
    2     FORMAT(4F20.0)
    3     FORMAT(2I5,F10.0)
    4     FORMAT(/,5X,'Z DOMAIN DENOMINATOR')
    5     FORMAT(/,5X,'Z DOMAIN NUMERATOR')
    6     FORMAT(I5,15A4)
    7     FORMAT(//5X,15A4,'POINTS = ',I5,//)
    8     FORMAT(5X,'THE SYSTEM IS',I3,' BY ',I3,' AND ',I3,'TH ORDER')
    9     FORMAT(8F10.0)
    11    FORMAT(//,5X,'VERIFY ',I2,' MODELS OF ORDER ',I2,//)
    12    FORMAT(10X,'ICNL = ',I2,/,10X,'IPLOT = ',I2,/,10X,'IDY = ',I2)
    13    FORMAT(10X,'MNVR = ',I2,///////)
    15    FORMAT(15A4)
    48    FORMAT(//,7X,'RMS  ERROR  ',I1,' = ',
        * F10.5,5X,'% RMS ERROR  =',E16.7,//)
    201   FORMAT(80A1)
    202   FORMAT(2X,////////////////////)
    203   FORMAT(2X,80('*'))
    204   FORMAT(5X,40('*'))
    415   FORMAT(//,5X,15A4,//)
    416   FORMAT(//,2X,15A4,//)
```

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```
6889  FORMAT(5E16.7)
C
      STOP
C
C     LIST OF VARIABLES
C
C     N     =  ORDER OF MODEL
C     NMOD  =  NUMBER OF H(Z) MODELS (TO BE VERIFIED WITH SINGLE CNL)
C              E.G., 10KN,15KN,& 20KN MODELS WITH 15 KN CNL
C     NAMEM=  MODEL TITLE CARD
C     NMAIO=  TITLE OF I/O SET
C     GAMMA=  PARAMETER VECTOR OF A MODEL
C     GAMMA1= STORAGE ARRAY IN WHICH ALL MODELS ARE STORED
C     ICNL=  1 IF CNL USED, 0 OTHERWISE
C     IPLOT=  1  IF CALCOMP PLOT DESIRED, 0 OTHERWISE
C     MNVR =  NUMBER OF INPUT OUTPUT SETS TO BE VERIFIED
C     X(K,J)= INPUTS;  J=1,...,NIO
C     Y(K,J)=  INPUTS;  J=1,...,MNVR
C     YREC(K,J)=  NCSL RESPONSES; J=1,...MNVR
C     UNL(K)=  NONLINEAR TABLE
C     RMS  =  RMS RECONSTRUCTION ERROR
C     PC   =PERCENT TOTAL ENERGY
C
C
      END
      SUBROUTINE PRVEC(A,N)
C     THIS SUBROUTINE OUTPUTS DOUBLE PRECISION SINGLE DIMENSIONED ARRAY
      DIMENSION A(1)
      DOUBLE PRECISION A
      WRITE(6,31)
      WRITE(6,1)(A(I),I=1,N)
1     FORMAT(1X,5G20.10)
      WRITE(6,31)
31    FORMAT(/)
      RETURN
      END
      SUBROUTINE NONLT(U,UNL,NPT)
      DIMENSION U(1),UNL(1)
      DO10 K=1,NPT
      UABS=ABS(U(K))
      I=UABS+1.0
      IP1=I+1
      UTEM=UNL(I)+(UABS-I+1.0)*(UNL(IP1)-UNL(I))
      U(K)=UTEM*U(K)/UABS
10    CONTINUE
      RETURN
      END
      SUBROUTINE RESPON(X,V,N,GAMMA,XLAMDA,MP1)
      DIMENSION X(1),V(1),GAMMA(1),XLAMDA(1)
      REAL*8 XSAV,GAMMA,XLAMDA
      NM1=N-1
      NP1=N+1
      NPNP1=N+N+1
      NPNP2=N+N+2
      DO19I=1,NPNP1
```

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```
19     XLAMDA(I)=0.0D00
       XSAV=0.0D00
       DO20K=1,MP1
       IF(N.EQ.1) GOTO25
       DO21I=1,NM1
       J=NP1-I
21     XLAMDA(J)=XLAMDA(J-1)
25     CONTINUE
       DO22I=1,N
       J=NPNP2-I
22     XLAMDA(J)=XLAMDA(J-1)
       XLAMDA(1)=XSAV
       XLAMDA(NP1)=V(K)
       XSAV=0.0D00
       DO23I=1,NPNP1
23     XSAV=XSAV-GAMMA(I+1)*XLAMDA(I)
       IF(DABS(XSAV).GE.1.0D10)XSAV=0.0D00
20     X(K)=XSAV
       RETURN
       END
       SUBROUTINE DASH(X,Y,N,INC,DL,SL)
C
C  THIS SUBROUTINE DRAWS A DASHED LINE DEFINED BY THE ARRAYS X AND Y.
C     X    IS THE ARRAY(1) CONTAINING THE X COORDINATES.
C     Y    IS THE ARRAY(1) CONTAINING THE Y COORDINATES.
C     N    IS THE NUMBER OF POINTS IN X AND Y.
C     INC  IS THE INCREMENT (CAN BE NEGATIVE, X AND Y WILL THEN USE NEGATI
C             ARGUMENTS, BUT N IS STILL POSITIVE).
C     DL   IS THE LENGTH OF THE DASH.
C     SL   IS THE LENGTH OF THE SPACE BETWEEN DASHES.
C
       REAL X(1),Y(1),R(2),P(20),Q(20)
       IF(N)6,5,4
4      IF(N-1)5,5,7
5      CALL PLOT(X,Y,N)
6      RETURN
7      L=1
       K=IABS(INC)
       M=1
       A=0.0
       R(1)=DL
       R(2)=SL
       P(1)=X(1)
       Q(1)=Y(1)
       I=1
       DO 38 J=2,N,K
       L=L+INC
18     I=I+1
       P(I)=X(L)
       Q(I)=Y(L)
       B=SQRT((P(I)-P(I-1))**2+(Q(I)-Q(I-1))**2)+A
       IF(B-R(M))33,26,23
23     A=(R(M)-A)/(B-A)
       P(I)=(P(I)-P(I-1))*A+P(I-1)
       Q(I)=(Q(I)-Q(I-1))*A+Q(I-1)
26     A=0.0D0
```

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```
      IF(M.EQ.1)CALL PLOT(P,Q,I)
      M=3-M
      P(1)=P(I)
      Q(1)=Q(I)
      I=1
      GO TO 18
33    IF(I-20)38,34,34
34    IF(M.EQ.1)CALL PLOT(P,Q,I)
      P(1)=P(I)
      Q(1)=Q(I)
      I=1
38    A=B
      IF(I.NE.1.AND.M.EQ.1)CALL PLOT(P,Q,I)
      GO TO 6
      END
      SUBROUTINE MYAXIS(XO,XF,YO,YF,NLD,NSD,TIC)
C
C    THIS SUBROUTINE PLOTS A TICKED LINE ON THE XY PLOTTER FROM (XO,YO)
C    (XF,YF) WITH NLD LARGE DIVISIONS AND NSD SMALL DIVISIONS PER LARGE
C    WITH A TIC OF SIZE TIC.
C
      REAL X(3),Y(3)
      DX=(XF-XO)/(NLD*NSD)
      DY=(YF-YO)/(NLD*NSD)
      A=SQRT(DX**2+DY**2)
      DXT=-TIC*DY/A
      DYT=TIC*DX/A
      X(3)=XO
      Y(3)=YO
      DO 20 I=1,NLD
      B=1.0
      DO 20 J=1,NSD
      X(1)=X(3)+B*DXT
      X(2)=X(3)
      X(3)=X(3)+DX
      Y(1)=Y(3)+B*DYT
      Y(2)=Y(3)
      Y(3)=Y(3)+DY
      CALL PLOT(X,Y,3)
20    B=0.5
      X(2)=X(3)+DXT
      Y(2)=Y(3)+DYT
      CALL PLOT(X(3),Y(3),2,-1)
      RETURN
      END
      SUBROUTINE SCALE(ND,NP,NF,X,NX,XO,XF)
C
C  THIS SUBROUTINE FINDS QUANTIZED UPPER AND LOWER LIMITS OF A DATA SET,
C  INPUT:
C  IN CHOOSING SCALES FOR GRAPHS.
C       ND IS THE NUMBER OF DIVISIONS (QUANTUM LEVELS).
C       NP IS THE NUMBER OF POINTS PER FUNCTION.
C       NF IS THE NUMBER OF FUNCTIONS.
C       X  IS THE ARRAY(NX,NF) CONTAINING THE FUNCTIONS.
C       NX IS THE DIMENSION OF X.
C  OUTPUT:
```

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```
C        XO IS THE LOWER LIMIT.
C        XF IS THE UPPER LIMIT.
C
      REAL X(NX,NF),XS(11)/1.,1.25,1.5,2.,2.5,3.,4.,5.,6.,8.,10./
      A=X(1,1)
      B=A
      DO 8 I=1,NF
      DO 8 J=1,NP
      IF(A.GT.X(J,I))A=X(J,I)
8     IF(B.LT.X(J,I))B=X(J,I)
      C=0.1*(ND-1)
      B=B-A
      IF(B.EQ.0.0)B=C
      IF(B.LE.C)GO TO 15
13    C=10.0*C
      IF(B.GT.C)GO TO 13
15    C=0.1*C
      IF(B.LE.C)GO TO 15
      B=B/C
      DO 20 I=1,11
      IF(B.LE.XS(I))GO TO 21
20    CONTINUE
21    B=XS(I)*C/(ND-1)
      XO=B*IFIX(A/B)
      IF(A.LT.0.0)XO=XO-B
      XF=XO+ND*B
      RETURN
      END
      SUBROUTINE PLOP8(NP,NF,DATA,ND,TO,T,NSZ,LABEL,INDEEP,BUFF)
C
C  THIS SUBROUTINE PLOTS ONE OR MORE FUNCTIONS OF A CONSTANT INTERVAL ON
C  X-Y PLOTTER.
C        NP      IS THE NUMBER OF POINTS PER FUNCTION.
C        NF      IS THE NUMBER OF FUNCTIONS.
C        DATA    IS THE ARRAY(ND,NF) CONTAINING THE FUNCTIONS.
C        ND      IS THE DIMENSION OF DATA.
C        TO      IS THE LOWEST VALUE OF THE INDEPENDENT VARIABLE.
C        T       IS THE INTERVAL BETWEEN TWO SAMPLE POINTS.
C        NSZ     IS THE NUMBER OF PLOTS PER PAGE (SIZE CONTROL).
C        LABEL   IS A HOLLERITH FIELD TO BE WRITTEN ACROSS THE TOP OF THE
C                (MUST END WITH A _).
C        INDEEP IS A HOLLERITH FEILD DESCRIBING THE INDEPENDENT VARIABLE
C                END WITH A _).
C        BUFF    IS A WORKING ARRAY(NP,NF+1)
C
      REAL DATA(ND,NF),TO,T,BUFF(NP,1),SLEFT/0.0/
      INTEGER LABEL(1),INDEEP(1),NSIZE/0/
      S=1.0/NSZ
      IF(SLEFT.GE.S.AND.NSZ.GE.NSIZE)GO TO 9
      CALL PICSIZ(16.0*S,28.0)
      SLEFT=1.0
      NSIZE=NSZ
9     CALL ORIGIN(14.0*S,28.0*(1.0-SLEFT)+S*2.5)
      CALL FACTOR(1.0/S,1.0/S)
      CALL MYAXIS(-12.0,0.0,0.0,0.0,12,5,-.25)
      CALL MYAXIS(0.0,0.0,0.0,20.0,10,5,-.5)
```

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1 3350 3900

```
      CALL MYAXIS(0.0,-12.0,20.0,20.0,12,5,-.25)
      CALL MYAXIS(-12.0,-12.0,20.0,0.0,10,5,-.5)
      CALL SCALE(12,NP,NF,DATA,ND,A,B)
      C=(B-A)/12.0
      DO 19 I=1,NF
      DO 19 J=1,NP
19    BUFF(J,I)=(A-DATA(J,I))/C
      N=NF+1
      A=20.0/(NP-1)
      DO 23 I=1,NP
23    BUFF(I,N)=(I-1)*A
      DO 26 I=1,13
      CALL NUMBER(I-12.825,-2.375,.25*S,B,90.0,3)
      B=B-C
26    IF(ABS(B).LE.1.0E-5*ABS(C))B=0.0
      A=(NP-1)*T*0.1
      B=TO-A
      DO 29 I=1,11
29    CALL NUMBER(.85,2.0*I-2.2,.25*S,I*A+B,90.0,3)
      CALL SYMBOL(1.6,4.0,.5*S,INDEEP,90.0)
      CALL SYMBOL(-12.75,-2.375,.4*S,LABEL,90.0)
      CALL PLOT(BUFF(NP,1),BUFF(NP,N),NP,-1)
      IF(NF.EQ.1)GO TO 46
      A=0.1
      B=0.2
      I=1
      J=1
      DO 45 K=2,NF
      CALL DASH(BUFF(J,K),BUFF(J,N),NP,I,B,A)
      B=0.5*B
      IF(B.GE.A)GO TO 44
      A=2.0*A
      B=2.0*A
44    I=-I
45    J=NP-J+1
46    SLEFT=SLEFT-S
      CALL FACTOR(1.0,1.0)
      RETURN
      END
//GO.PLOTMSG DD SYSOUT=A
//GO.PLOTTER DD SYSOUT=P
//GO.SYSIN DD *
    2     1
    1     1
    5
//
END OF DATA
```